Doctoral Program in Physiology

Department of Physiology

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The potential of elastic bands to optimize ocular and cardiovascular responses, subjective effort, and performance in squats

International Doctoral Thesis presented by:

Javier Gené Morales

Directed by:

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Certify that:

The present dissertation, entitled **"The potential of elastic bands to optimize ocular and cardiovascular responses, subjective effort, and performance in squats"** has been written under their supervision by D. Javier Gené Morales. This manuscript corresponds to the Doctoral Program with International Mention in Physiology of the University of Valencia.

In recognition whereof, we sign the present certificate in Valencia, February 2022.

Juan Carlos Colado Sánchez   Andrés Gené Sampedro   Rosario Salvador Palmer

Acknowledgments

The man who moves a mountain begins by carrying away small stones.

Chinese proverb

To you, for using a part of your time to read this thesis.

To my parents, for being an "in-vivo model" to follow.

I am not an actual fan of cinema. However, these days, resting from endless writing sessions, I have been watching *The Lord of the Rings* trilogy. It came to my mind to compare the doctoral process with the journey of Frodo, who must deposit the ring in a volcano. The process comes to an end when the ring (or in this case, the manuscript) is deposited. However, a whole new life begins after that. Of course, the person depositing the ring or the manuscript is central to the process, but how far could Frodo have gone on his own? He would have gotten nowhere.

As a Chinese proverb states, a journey of a thousand miles begins with a single step. I remember my first presentation at an online conference with my father and my brother. It was summer, and we were wearing a smart shirt-and-tie combination with swimming trunks instead of trousers. I thank Johanna for the invitation to the conference and the kind treatment we have always received from her.

Apart from the beauty of my dissertation journey itself, the greatest treasure is the people I have met throughout who have offered me their unconditional help. Thank you Dr. Jorge Jorge, Dr. Travis Triplett, Dr. Mile Ćavar, and Dr. Jeff McBride for being my support out of home. Nothing would have been possible without you. Additionally, it is worth mentioning Dr. Francisco Alonso and Dr. Sergio Useche for the constant learning opportunities with which they provide me.

The further the process progresses or the closer one gets to Mordor, increasingly complex issues appear. One of the main issues to deal with in this process has been combining the development of the thesis, my job, and my personal life. In brief, when facing these issues one learns to "play around" with them. As I have discussed with several colleagues, we would not be here if we were not enjoying ourselves. I have spent so many hours working with my laptop at bars and pubs, and so much time celebrating with friends while writing manuscripts or cleaning data. I have taken so many trips carrying my computer through Europe, Chile, China, the United States, and Australia just to take advantage of a plane, car, or train trip to progress in the thesis process.

Again, returning to the comparison with *The Lord of the Rings*, what would Frodo be without the precious company of his Hobbit friends? I thank Álvaro, Ángel, Jeff, Pedro, and all the members of the Prevention and Health in Exercise and Sport (PHES) and Development and Advising in Traffic Safety (DATS) research groups. Additionally, to my brother Andrés, Héctor, and Cristina: I appreciate your interest and unconditional support. Hermes, Amposta, Edu, Dani, Susi, Toni, Jorge, and Zurano—there are so many people to mention. Of course, I am thankful to my partner, Rosa. Finally, you will confirm that I was actually doing a PhD. Luckily, there is much left for you to put up with from this journey. Thank you!

Last but not least (indeed, completely the opposite), the Fellowship of the Ring should be mentioned. They help Frodo safely walk his path. I thank my thesis directors Dr. Rosario Salvador Palmer, Dr. Juan Carlos Colado Sánchez, and Dr. Andrés Gené Sampedro, my father. With your sword, bow, and axe, you have supported me in the best way for this process to be smooth and to extract maximum learning. You have made everything so easy for me; I truly thank you. Finally, I must mention Carmen, my mother. She is actually comparable to the wizard Gandalf. While dealing with a thousand things external to my thesis process which are of utmost importance, she has given me her almost magical support to continue.

Thank you all.

We are still on the way.

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La persona que mueve una montaña comienza cargando piedras pequeñas.

Proverbio chino

A ti, que estás empleando una parte de tu tiempo en leer esta tesis.

A mis padres por ser un "modelo in-vivo" a seguir.

No soy muy aficionado al cine, pero estos últimos días, en descansos de interminables sesiones de escritura, he estado viendo la trilogía de *El Señor de los Anillos*. Se me ocurre hacer un símil del proceso de doctorado con el viaje del señor Frodo, que debe depositar el anillo en un volcán. El fin del proceso es depositar el anillo (o el manuscrito en este caso), pero toda una nueva vida empieza a partir de ello. Por supuesto, la persona más laureada en todo este proceso es quien deposita el anillo, o el manuscrito, pero ¿hasta dónde hubiera sido capaz de llegar solo? A ningún sitio.

Como bien dice el proverbio chino, un viaje de mil millas empieza con un solo paso. Recuerdo aquella primera presentación en un congreso online, con mi padre y mi hermano, un verano, con camisa, corbata, y bañador debajo. Gracias Johanna por la invitación y el trato que siempre nos has ofrecido.

Además de lo bonito del propio camino, el mayor tesoro es la gente que he ido encontrando en él. Gente que me ha ofrecido su ayuda de manera desinteresada. Gracias al Dr. Jorge Jorge, Dra. Travis Triplett, Dr. Mile Ćavar y Dr. Jeff McBride, por haber sido mi enlace fuera de España, sin vosotros, nada de esto hubiera continuado hacia adelante. También cabe mencionar al Dr. Francisco Alonso y Dr. Sergio Useche, por la oportunidad de aprendizaje constante que me brindan.

Cuanto más se avanza en el proceso, cuanto más cerca de Mordor (sí, continúa el símil con *El Señor de los Anillos*), más asuntos y de mayor dificultad aparecen. Uno de los principales asuntos a gestionar podría ser el compaginar el desarrollo de la tesis con el trabajo, y todo esto con la vida personal. Aunque al final, se aprende a "jugar" con ello. Como hablo con muchos compañeros: no estaríamos aquí si no disfrutáramos. Cuántas horas "trabarjando", cuántos días de celebración con amigos y con el portátil pasando datos o redactando. Cuántos viajes cargando con el ordenador por Europa, Chile, China, Estados Unidos, Australia para sacar provecho de cada rato de avión, coche o tren y avanzar.

De nuevo, si volvemos a la comparación con El Señor de los Anillos, ¿qué sería Frodo sin la compañía de sus amigos Hobbits? Gracias Álvaro, Ángel, Jeff, Pedro, y todos los miembros de los grupos de investigación *Prevention and Health in Exercise and Sport* (PHES) y *Development and Advising in Traffic Safety* (DATS). También mi hermano Andrés, Héctor y Cristina, gracias por el interés y el apoyo incondicional. Hermes, Amposta, Edu, Dani, Susi, Toni, Jorge, Zurano, tanta gente que mencionar. Por supuesto, agradecido a mi pareja, Rosa. Por fin vas a comprobar que es verdad que estaba haciendo un doctorado. Por suerte, aún te queda mucho por aguantar de este camino. Gracias.

Por último, y no por ello menos importante (de hecho, al revés), correspondería mencionar a la comunidad del anillo, que ayuda a que Frodo pueda recorrer el camino seguro. Gracias a mis directores de tesis, Dra. Rosario Salvador Palmer, Dr. Juan Carlos Colado Sánchez y Dr. Andrés Gené Sampedro, mi padre. Con vuestra espada, arco y hacha me habéis apoyado de la mejor manera para que este proceso sea fluido y poder extraer el máximo aprendizaje. Me lo habéis puesto todo muy fácil, gracias, de verdad. Como última mención, Carmen, mi madre, ella sí que podría ser comparable a Gandalf, el mago. A la vez que lidia con mil cosas externas a mi proceso de tesis, y que son de suma importancia, me da su apoyo casi mágico para continuar.

Gracias a todas y todos,

Seguimos en camino.

Summary

Introduction

Physical exercise and sports practice are common habits in most population groups. Physical exercise and more specifically resistance training have innumerable benefits for health and performance. To maximize these benefits, it is necessary to evaluate performance and physiological adaptations that can be achieved depending on the methodological features of the activity or exercise performed.

As presented in **Chapter 1**, different training program variables (e.g., exercise selection, intensity, volume, effort level, and materials used) produce different responses. Therefore, the study of varied training methodologies is required. The squat is one of the most commonly selected exercises for resistance training routines due to its similarity to a wide range of athletic and everyday activities. Each different squat variation presents different biomechanical characteristics and entails different neuromuscular acute effects. Consequently, it is necessary to study the squat exercise and its different variations to deeply understand the movement and to individualize resistance training programs. Concerning materials, elastic bands are increasing in popularity for resistance training with both health and performance purposes.

Elastic bands provide greater resistance (more kilograms) when they are longer and fewer kilograms when they are shortened. Accordingly, from a performance perspective, elastic bands can provide optimum resistance throughout the range of motion in squats. For squats, elastic bands are usually attached to the bar to provide the pertinent resistance measured at the participant’s standing position, as is done when using weight plates to load the bar. Therefore, the weight at the participant’s standing position is the same whether one uses elastic bands or weight plates. However, elastic bands provide less weight throughout the range of movement below this point. This makes the comparison between elastic bands and weight plates in terms of used resistance uneven.

Within the range of motion of certain resistance training exercises such as the squat, there exists the so-called sticking region. The sticking region is defined as the part of the range of motion in which a disproportionally large increase in difficulty occurs, and this is considered a mechanical constraint. Bearing this in mind, the question arises whether elastic bands could be attached to the bar right above the sticking point (the point at which the sticking region ends) to provide the pertinent weight. This would make it possible to obtain less weight in the parts of the range of motion that are biomechanically disadvantageous and more weight in the

biomechanically efficient parts of the exercise. Attaching the elastic bands to the bar immediately above the sticking point would therefore result in more weight during more degrees of movement and less weight during fewer degrees of movement compared to weight plates. Therefore, this way of applying the elastic bands could be a useful strategy to overcome the squat sticking point and enhance performance. This new methodology could allow participants to perform more repetitions with more weight compared with what they would be able to move with weight plates. To the best of our knowledge, no previous research has evaluated the effects of attaching the elastic bands to the bar immediately above the squat sticking point. The elastic bands would therefore be providing the pertinent weight at the sticking point instead of at the standing position of the participant.

Focusing on health, resistance training has been shown to influence cardiovascular and ocular parameters both acutely and chronically. This influence on cardiovascular (e.g., systolic and diastolic blood pressure, mean arterial blood pressure, pulse pressure) and ocular parameters (e.g., intraocular pressure, ocular perfusion pressure) could vary depending on training program variables such as the weight used, the level of effort, or the materials used. These cardiovascular and ocular acute adaptations could be detrimental rather than beneficial for the development and progression of cardiovascular conditions associated with blood pressure such as hypertension, which is the leading modifiable risk factor for cardiovascular disease and premature death. Furthermore, dramatic increases or fluctuations of intraocular pressure and/or ocular perfusion pressure decreases could entail a risk for the development of ocular conditions such as primary open-angle glaucoma, which is the second most common cause of irreversible blindness worldwide.

Responses of the cardiovascular system to physical exercise have been widely studied with relatively homogeneous results. On the other hand, there is controversy regarding the intraocular pressure behavior with certain physical exercise methodologies such as resistance training, including the squat. While several studies indicate that intraocular pressure increases and ocular perfusion pressure decreases with resistance training, other research has found the opposite. It is worth highlighting that in the deepest phases of the squat, the intraabdominal pressure rises, and this could lead to intracranial pressure and intraocular pressure elevation. Therefore, considering that elastic bands modify the kilograms provided throughout the range of motion, the question arises whether the use of elastic bands to load the bar in squats may provoke different cardiovascular and/or ocular acute adaptations compared to traditional resistance training devices (in particular, weight plates). Furthermore, numerous studies have shown that sex, age, central corneal thickness, and baseline levels of intraocular pressure, *inter* *alia*, could be correlated with intraocular pressure levels and fluctuations. In consequence, it is crucial to understand the moderating role that sociodemographic and physiological variables can play in individual variations of intraocular pressure with exercise. We did not find previous studies analyzing the prediction potential of sex, age, baseline levels of intraocular pressure, and baseline levels of central corneal thickness in the variations of intraocular pressure caused by exercise.

Aims

Bearing in mind what has been mentioned in the introduction, the compendium composing the present doctoral thesis was aimed at assessing the potential use of elastic bands to load the bar in squats and its relationship with ocular and cardiovascular health parameters, subjective effort, and performance. Additionally, two preliminary studies were designed to identify potential predictors of the intraocular pressure variations after exercise and to select the most appropriate squat variation for the present project, respectively.

The study design, main results, and conclusions of each of the four articles included in the compendium, which justify the original contribution of the present doctoral thesis, are presented below.

First study: The potential of sex, age, and baseline intraocular pressure to predict intraocular pressure variations with exercise

The first article of the compendium is included in **Chapter 2**. It was aimed at identifying mediator parameters in the intraocular pressure changes after exercise. For this purpose, a multiple linear regression was conducted with age, sex, baseline intraocular pressure levels, and baseline central corneal thickness levels as potential predictors of intraocular pressure variations after a 90-minute acrobatic gymnastics session.

Forty-nine healthy gymnasts with at least six months of experience (63.27% females, age: 27.67 ± 7.10 years, range: 18–40 years) voluntarily agreed to participate in the study. Two sessions were conducted. One session was used for familiarization and to confirm the suitability of the participants for the study according to the inclusion criteria. The second session was conducted to complete the research procedures. In this experimental session, measurements of the selected variables (intraocular pressure, central corneal thickness) were performed before the training session and between 5 and 10 minutes after finishing the exercise. The session lasted 90 minutes. For the statistical analyses, participants were divided according to their sex and age with groups of young adults (≤ 25 years) and adults (> 25 years).

Furthermore, participants were stratified into three groups according to their resting intraocular pressure levels (low, medium, or high). For this purpose, preexercise intraocular pressure levels of the sample were divided into terciles (with limits at 14 and 17 mmHg). A mixed-factorial analysis of variance (ANOVA) evaluated differences between groups and between the preexercise and postexercise values. Sex, age, and intraocular pressure levels were included as the between-subject factors. On the other hand, exercise was used as the within-subject factor. In addition, a multiple linear regression was conducted to potentially predict the intraocular pressure variations due to the exercise. The level of significance was uniformly established at $p < 0.05$.

The results of this study show that intraocular pressure levels obtained after the training session were significantly lower than preexercise values ($p < 0.001$, effect size: 0.73). Central corneal thickness was not significantly modified due to the exercise effect ($p = 0.229$). It is worth highlighting that baseline intraocular pressure ($p = 0.007$) and sex ($p = 0.001$) appeared as significant predictors of the intraocular pressure variations with exercise. More specifically, males, participants older than 25 years, and participants with baseline intraocular pressure levels above 14 mmHg experienced significant decreases in the postexercise values compared with preexercise values ($p \leq 0.001$ in all cases, effect sizes between 0.57 and 1.02). In contrast, females, participants younger than 25 years, and participants with resting intraocular pressure levels equal or below 14 mmHg did not show significant intraocular pressure variations after the exercise (significance levels [*p*] between 0.114 y 0.312). Significant differences in the intraocular pressure variations were observed between the participants with resting intraocular pressure equal to or below 14 mmHg and subjects with resting intraocular pressure equal to or above 17 mmHg ($p = 0.008$, effect sizes: 0.96).

These results confirm that intraocular pressure behavior after exercise is multifactorial. Professionals working with people at risk of suffering high intraocular pressure should account for individual difference such as age, sex, and baseline intraocular pressure levels when programming training adapted to each subject situation.

Second study: Characterization of the main squat variations

The second article of the compendium, which is presented in **Chapter 3**, gathers biomechanical, kinetic, and myoelectric information about the most common squat variations (i.e., high-bar back squat, low-bar back squat, front squat, overhead squat, and guided squat). This study aimed to obtain scientific information to select the most appropriate squat variation to be included as a reference in the subsequent studies of the present doctoral thesis.

A systematic review of the literature was conducted using four databases and different manual searches. Thirty articles were retrieved after filtering according to the eligibility criteria. The quality of the included studies was assessed with the Physiotherapy Evidence Database (PEDro) scale. All studies obtained scores of between 5 and 6 points out of 6 possible points. Selected squat variations were the high-bar back squat (analyzed by 26 articles), low-bar back squat (analyzed by one article), front squat (analyzed by five articles), overhead squat (analyzed by two articles), and guided squat performed using a Smith machine (analyzed by two articles). Gluteus maximus, gluteus medialis, adductors, vastus lateralis, vastus medialis, rectus femoris, biceps femoris, semitendinosus, tibialis anterior, gastrocnemius, and soleus were included as muscles acting on the hips, knees, and ankles.

All variations of the squat exercise begin with the participant in the standing position. Synergistic hip, knee, and ankle flexion is performed followed by extension in the ascent, which ends with the participant in the starting position. The results of the present study indicate that the squat is a knee extensors-predominant exercise, meaning that it mainly exercises the muscles of the quadriceps (vastus lateralis, vastus medialis, rectus femoris, and vastus intermedius). Although the muscles of the quadriceps are the main target of the squat exercise, modifications in the bar placement such as in the low-bar back squat can increase the activity of the hip extensors muscles. Most of the consulted investigations (26 articles) analyzed the high-bar back squat with relatively homogeneous results in terms of activation patterns. The load was identified as the major determinant of muscle activation levels. Furthermore, different technical modifications (movement depth, width of stance, hip rotation, and feet orientation) entailed different activation patterns.

After the analysis was performed, the guided high-bar back squat performed using a Smith machine was selected for inclusion in the methodology of the other two studies of the present doctoral thesis analyzing the squat. Concerning the technical execution, parallel depth (as per the lines drawn by the femur and the ground) and neutral positions of stance width, hip rotation, and feet orientation were selected.

Third study: The potential of elastic bands to maximize performance in squats

The third article of the compendium, which comprises **Chapter 4**, tests a new method of loading the bar with elastic bands in squats. The pertinent weight that each participant had to use according to their one-repetition maximum percentage was added to the bar at the standing position or just above each participant's knee sticking point using exclusively elastic bands.

Twenty healthy, physically active males, with at least one year of experience in resistance training (age: 25.50 ± 5.26 years; body mass index: 24.09 ± 2.06 kg/m^2; body fat: 10.16 ± 2.23%; squat one-repetition maximum: 127.10 ± 24.10 kg; ratio one-repetition maximum to body weight [relative strength]: 1.70 ± 0.36) participated in three sessions: two for assessment and familiarization and one experimental. In the experimental session, six series of squats were performed in random order (three sets using only weight plates to load the bar and three using only elastic bands to load the bar). Four sets (two using weight plates to load the bar and two using elastic bands) were performed until muscular failure, and two sets (one using weight plates to load the bar and one using elastic bands) consisted of submaximal efforts. A goniometer was used to measure the angle of the knee sticking point, and the height of the barbell at this point was marked. Elastic bands were attached to the bar just above this point of the range of motion in the pertinent condition. The weight at the standing position, number of repetitions performed, heart rate, blood pressure, and rate of perceived effort were measured immediately after the completion of each set. An analysis of variance of one-way repeated measurements with Bonferroni adjustments and nonparametric Friedman and Wilcoxon tests were conducted to evaluate differences between the study variables in the different squat conditions. The level of significance was uniformly established at $p < 0.05$.

When weights were equated at the standing position between weight plates and elastic bands, elastic bands permitted participants to perform approximately eight more repetitions ($p < 0.001$; effect size: 2.44) with the same weight at the standing position (less at the deepest positions), with similar internal load responses (i.e., blood pressure, rate of perceived exertion) compared to weight plates. On the other hand, when weights were equated just above the sticking point between weight plates and elastic bands, elastic bands allowed participants to perform approximately three more repetitions ($p = 0.001$, effect size: 1.27) with approximately 25% more kilograms ($p = 0.001$, effect size: 1.15) at the standing position (same kilograms at the sticking point and less kilograms below the sticking point) with similar blood pressure and heart rate responses ($p > 0.05$).

These results confirm that elastic bands could be an optimal material to load the bar for squats for young, trained males. Furthermore, the results suggest that the methodology of adding the pertinent weight just above the sticking point using elastic bands could be useful to increase squat performance. This would be obtained through the overcoming of the biomechanically disadvantageous phase of the squat in which technique is compromised and failure occurs. The findings of this study establish the foundation for future research regarding using elastic bands to improve physical performance. Among other future research lines, medium- or long-term intervention studies should evaluate the potential of the training stimulus provided by the elastic bands attached to the bar immediately above the sticking point in the squat and/or other resistance training exercises to produce chronic adaptations. Additionally, it would be interesting to evaluate whether the same increase in weight and number of repetitions is obtained when directly adding 25% more weight at the participant's standing position compared to the methodology of loading the bar just above the sticking point.

Fourth study: Elastic bands as a device to provoke conservative ocular and cardiovascular responses

With the results of Chapters 2, 3, and 4 in mind, the fourth and last published article of the compendium, which comprises **Chapter 5**, assessed the potential ocular and cardiovascular responses after squatting using elastic bands to load the bar. Additionally, the study evaluated whether these physiological responses were similar compared to those squatting using weight plates. The main aim of the study was to examine ocular (intraocular pressure, ocular perfusion pressure, and central corneal thickness) and cardiovascular (mean blood pressure, pulse pressure, and heart rate) responses produced by squatting using weight plates or elastic bands to load the bar. Furthermore, the responses after a maximal or submaximal effort level were compared.

Twenty healthy, physically active males with at least one year of experience in resistance training voluntarily participated in the study (age: 25.55 ± 4.75 years; body mass: 75.67 ± 9.02 kg; body mass index: 24.04 ± 2.11 kg/m^2; body fat: 10.19 ± 2.29%; kilograms for one-repetition maximum: 126.53 ± 24.62 kg; ratio one-repetition maximum to body weight [relative strength]: 1.68 ± 0.35). Two sessions were conducted: one for assessment and familiarization and one experimental trial. In the experimental session, the participants performed repetitions to failure and submaximal repetitions at 75% of their one-repetition maximum using weight plates or elastic bands (added at the participants' standing position) to load the bar. A total of four different sets were performed (two using elastic bands to load the bar and two using weight plates). Preexercise measurements of each cardiovascular and ocular parameter were taken. Each of the four sets was then performed in random order after a standardized warm-up. Cardiovascular measurements were taken immediately after the completion of each set. Ocular measurements were uniformly started one minute after the exercise. An analysis of variance of two-way repeated measurements evaluated differences between the squat conditions performed. The material used (elastic bands or weight plates) and effort level (maximal or submaximal) were used as the within-subject factors. A significance level of $p < 0.05$ was established.

Elastic bands permitted performing more repetitions with the same weight at the standing position (fewer at the deepest phases of the squat) compared to weight plates. Regarding the physiological parameters analyzed related to the present doctoral thesis, intraocular pressure was significantly lower than before the exercise (effect sizes between 0.73 and 1.00). Similarly, mean ocular perfusion pressure (effect sizes between 1.14 and 1.36), heart rate (effect sizes between 2.42 and 2.77), pulse pressure (effect sizes between 0.80 and 1.32), and mean arterial blood pressure (effect sizes between 0.85 and 1.16) were significantly higher compared with preexercise values. On the other hand, central corneal thickness did not significantly vary ($p = 0.828$). Cardiovascular and ocular responses were similar ($p > 0.05$) for the use of weight plates (fewer repetitions, more average weight) and elastic bands (more repetitions, less average weight). Although no effect of the material was observed in the ocular variables ($p > 0.05$), the major intraocular pressure descent (2.70 mmHg) was obtained after performing the maximum number of repetitions with elastic bands; a tendency of statistical significance was observed in the comparison with the condition consisting of a maximal number of repetitions with weight plates (mean difference: 0.55 mmHg, 95% confidence interval [-0.12–1.22], $p = 0.10$, effect size: 0.21). Therefore, elastic bands seem an appropriate device to load the bar in squats for subjects who should avoid intraocular pressure increments.

To supplement these results, future studies should compare intraocular pressure variations throughout the range of motion when using weight plates or elastic bands to load the bar using a continuous monitoring device to differentiate between the movement phases (e.g., concentric and eccentric). Additionally, chronic intraocular pressure and ocular perfusion pressure adaptations to resistance training with elastic bands in healthy subjects, older subjects, subjects at risk of suffering glaucoma, and subjects with diagnosed glaucoma should be evaluated.

The findings of the present research suggest that the total amount of work (repetitions x weight) could condition ocular and cardiovascular responses. It is recommended to control technique and movement tempo and avoid the Valsalva maneuver with the aim of maintaining conservative intraocular pressure responses. With this in mind, elastic bands and weight plates could be interchangeably used to load the bar in squats in terms of ocular and cardiovascular responses. Optometrists, ophthalmologists, and strength and conditioning professionals working with people at risk of suffering elevated intraocular pressure or other factors associated with glaucoma development could find the findings of this study useful.

Conclusions

The findings of the present doctoral thesis shown through the results of the four articles developed establish a foundation for future research with elastic bands from a performance approach. Similarly, results obtained regarding ocular and cardiovascular health parameters open new paths to understanding external (training programming variables) and internal (sociodemographic and physiological) factors potentially conditioning physiological acute adaptations to exercise.

Responding to the hypotheses of the present thesis, the main conclusions to highlight are presented hereafter. First, the intraocular pressure after performing an acrobatic gymnastics training session is lower than preexercise values, obtaining significant differences between sexes, age groups, and groups based on baseline intraocular pressure. Baseline intraocular pressure levels and sex were encountered as significant predictors of the intraocular pressure variations provoked by exercise. Second, elastic bands, when attached to the bar with the pertinent weight just above the sticking point, make it possible to use 25% more weight at the standing position and perform approximately three more repetitions compared to weight plates with nonsignificant differences in blood pressure and heart rate. Third, the intraocular pressure after squatting is lower compared with preexercise values, and mean ocular perfusion pressure, pulse pressure, and mean arterial blood pressure are higher with nonsignificant differences between using elastic bands or weight plates to load the bar.

The compendium of articles composing the present doctoral thesis illuminates the potential use of elastic bands to maximize performance and maintain conservative ocular and cardiovascular responses. It also contributes to the multidisciplinary collaboration between strength and conditioning professionals, optometrists, and ophthalmologists to raise awareness of the importance of the prevention, management, and control of risk factors associated with glaucoma such as elevated intraocular pressure or fluctuations, decreased ocular perfusion pressure, and increased or decreased blood pressure.

Resumen

Introducción

La práctica de ejercicio físico y actividades deportivas es cada vez más habitual en la población general. El ejercicio físico y, de manera más específica el entrenamiento de la fuerza, presenta numerosos beneficios para la salud y el rendimiento de las personas. En pro de maximizar estos beneficios, se hace necesario evaluar las diferentes adaptaciones fisiológicas y de rendimiento que se pueden dar en base a las características metodológicas de la actividad o ejercicio realizados.

Tal como se muestra en el **Capítulo 1**, existen diferentes variables de programación del entrenamiento (por ejemplo, selección de ejercicio, intensidad, volumen, carácter del esfuerzo y material empleado) que conllevarán diferentes respuestas fisiológicas y de rendimiento. Por tanto, es necesario analizar una variedad de metodologías. En este sentido, la sentadilla es uno de los ejercicios más seleccionados para rutinas de entrenamiento de la fuerza debido a su similitud con un amplio rango de actividades atléticas y del día a día. Las diferentes variantes de la sentadilla presentan diferentes características biomecánicas y diferentes efectos neuromusculares agudos. En consecuencia, el estudio de la sentadilla y sus diferentes variantes es necesario para comprender en profundidad el movimiento e individualizar los programas de entrenamiento de la fuerza. En cuanto al material, las bandas elásticas están incrementando en popularidad para el entrenamiento de la fuerza, tanto con objetivos de salud, como de rendimiento.

Las bandas elásticas aportan una mayor resistencia (más kilogramos) cuando su longitud es mayor y menos kilogramos cuando su longitud es menor. Por tanto, desde una perspectiva de rendimiento en el ejercicio de la sentadilla, las bandas elásticas podrían proporcionar una resistencia óptima a lo largo del rango de movimiento. En este sentido, para realizar sentadillas, las bandas elásticas se suelen cargar a la barra con el peso correspondiente en la posición de bipedestación del participante, como se suele hacer cuando se utilizan discos para cargar la barra. Por tanto, los kilogramos que el participante está utilizando en bipedestación serían los mismos independientemente de que se usen bandas elásticas o discos. Sin embargo, durante todo el rango de movimiento por debajo de este punto, las bandas elásticas estarían aportando menos peso que los discos y, por tanto, la comparación en cuanto a resistencia movilizada quedaría descompensada.

Dentro del rango de movimiento de algunos ejercicios de fuerza, como la sentadilla, existe la llamada zona de estancamiento (*sticking region*). La zona de estancamiento se define

como la parte del rango de movimiento en la que tiene lugar un aumento desproporcionado de la dificultad para realizar el movimiento, debido a factores biomecánicos. Con esto en mente, surge la cuestión de si las bandas elásticas pudieran ser cargadas a la barra con los kilogramos correspondientes justo por encima del punto de estancamiento (*sticking point,* punto en el que se termina la zona de estancamiento) para obtener menos peso en las partes del rango de movimiento que son biomecánicamente desventajosas y más peso en las partes que son biomecánicamente eficientes. Esta aplicación de las bandas elásticas podría resultar en más peso durante más grados de movimiento y menos peso durante menos grados de movimiento en comparación con el uso de discos. Por tanto, esta manera de aplicar las bandas elásticas podría ser una estrategia útil para superar el punto de estancamiento (*sticking point*) en el ejercicio de sentadilla y maximizar el rendimiento. Esta nueva metodología de aplicar las bandas elásticas podría permitir a los participantes realizar más repeticiones y obtener más peso del que serían capaces de movilizar utilizando discos para cargar la barra. Ningún estudio previo ha evaluado los efectos de cargar las bandas elásticas a la barra con el peso pertinentes por encima del punto de estancamiento en la sentadilla.

Enfocándonos en salud, el entrenamiento de la fuerza ha mostrado tener influencia en parámetros oculares y cardiovasculares, tanto de manera aguda como crónica. Esta influencia en parámetros cardiovasculares (por ejemplo, presión arterial sistólica y diastólica, presión arterial media, presión del pulso, etcétera) y oculares (por ejemplo, presión intraocular y presión de perfusión ocular) difiere dependiendo de las variables de programación del entrenamiento, como, por ejemplo, el peso utilizado, el carácter del esfuerzo y el material empleado. En este sentido, algunas de estas adaptaciones agudas cardiovasculares y oculares, en lugar de beneficiosas, podrían ser peligrosas para el desarrollo y progresión de enfermedades. Entre ellas, aparecen enfermedades cardiovasculares asociadas con la presión arterial elevada, como puede ser la hipertensión, factor principal modificable para enfermedad cardiovascular y muerte prematura. También, aumentos drásticos o fluctuaciones de presión intraocular y/o disminuciones de presión de perfusión ocular podrían suponer un riesgo para el desarrollo de enfermedades oculares, como lo es el glaucoma primario de ángulo abierto, segunda causa de ceguera irreversible en todo el mundo.

El comportamiento de parámetros cardiovasculares con ejercicio ha sido estudiado en mayor medida con resultados homogéneos. Por lo contrario, existe cierta controversia en cuanto al comportamiento de la presión intraocular con ciertas metodologías de ejercicio físico, tales como el entrenamiento de la fuerza, incluyendo el ejercicio de sentadilla. Mientras que algunos estudios aseguran aumentos de presión intraocular y reducciones de presión de perfusión ocular con el entrenamiento de fuerza, otras investigaciones detectaron disminuciones en estos parámetros. Cabe destacar, que en las fases más profundas de la sentadilla se dan aumentos de presión intraabdominal y que esto, podría dar lugar a aumentos de la presión intracraneal y presión intraocular. Por tanto, teniendo en mente que las bandas elásticas modifican los kilogramos utilizados a lo largo del rango de movimiento, surge la pregunta de si utilizar bandas elásticas para cargar la barra en sentadillas podría producir diferentes respuestas agudas oculares y/o cardiovasculares en comparación con los dispositivos de entrenamiento tradicionales (en particular, discos). Además, numerosos estudios han mostrado que el sexo, la edad, el espesor corneal central y los niveles basales de presión intraocular, entre otros parámetros, pueden estar correlacionados con los niveles de presión intraocular y sus fluctuaciones. Por consiguiente, es crucial conocer el rol moderador que variables sociodemográficas y fisiológicas pueden tener en las variaciones individuales de presión intraocular debido al ejercicio. No se han encontrado estudios previos analizando el potencial predictor del sexo, la edad, los niveles de reposo de presión intraocular y de espesor corneal central en las variaciones de presión intraocular tras la práctica de ejercicio físico.

Objetivos

Tomando en consideración lo mencionado en la introducción, el compendio de artículos que constituye la presente tesis doctoral tiene el objetivo de evaluar el uso potencial de las bandas elásticas para cargar la barra en sentadillas y su relación con parámetros de salud ocular y cardiovascular, esfuerzo subjetivo y rendimiento. Además, se diseñaron dos estudios preliminares para identificar predictores potenciales de las variaciones de presión intraocular tras el ejercicio y para seleccionar la variación de sentadilla más apropiada para el presente proyecto, respectivamente.

A continuación, se muestra el diseño, los principales resultados y las conclusiones de cada uno de los cuatro artículos dentro del compendio, justificativos de la aportación original de esta tesis.

Primer estudio: El potencial del sexo, la edad y los niveles basales de presión intraocular para predecir las variaciones de presión intraocular con ejercicio

El primer artículo del compendio está incluido en el **Capítulo 2**. Este tenía el objetivo de identificar y profundizar en parámetros mediadores en los cambios de presión intraocular después del ejercicio. Para este propósito, una regresión lineal múltiple se llevó a cabo con la edad, sexo, niveles basales de presión intraocular y niveles basales de espesor corneal central como potenciales predictores de las variaciones de presión intraocular tras una sesión de noventa minutos de gimnasia acrobática.

Cuarenta y nueve gimnastas, con experiencia de al menos seis meses y con buena salud ocular (63.27% mujeres, edad: 27.67 ± 7.10 años, rango: 18 - 40 años) accedieron a participar en el estudio de manera voluntaria. Se llevaron a cabo dos sesiones, una de familiarización para confirmar la validez de los participantes para el estudio según los criterios de inclusión, y una sesión experimental para llevar a cabo los procedimientos de investigación. En la sesión experimental se tomaron medidas de las variables seleccionadas para el estudio, antes de la sesión de entrenamiento y entre 5 y 10 minutos al terminar el ejercicio. La sesión tenía una duración de 90 minutos. Para los análisis estadísticos, los participantes fueron divididos según sexo y edad, en adultos jóvenes (≤ 25 años) y adultos (> 25 años). De la misma manera, se dividió a los sujetos en tres grupos en función de los niveles de presión intraocular de reposo (bajos, medios y altos). Para ello, los niveles de presión intraocular obtenidos antes del ejercicio se dividieron en terciles (con límites en 14 y 17 mmHg). Un análisis de la varianza (ANOVA) mixto factorial evaluó diferencias entre grupos y entre valores antes y después del ejercicio. Se determinaron el sexo, la edad y los niveles basales de presión intraocular como factores inter-sujeto y el ejercicio como factor intra-sujeto. Además, se llevó a cabo una regresión lineal múltiple para potencialmente predecir las variaciones de presión intraocular por efecto del ejercicio físico. El nivel de significancia fue uniformemente establecido en $p < 0.05$.

Los resultados mostraron que los niveles de presión intraocular obtenidos tras la sesión de entrenamiento eran significativamente menores que los niveles medidos antes del ejercicio ($p < 0.001$, tamaño del efecto: 0.73) y que el espesor corneal central no se modificó de manera significativa ($p = 0.229$). Cabe destacar que los niveles de reposo de presión intraocular ($p = 0.007$) y el sexo ($p = 0.001$) aparecieron como predictores significativos de las variaciones de presión intraocular debidas al ejercicio. De manera más específica, los hombres, los sujetos mayores de 25 años y los sujetos con niveles de presión intraocular de reposo por encima de 14 mmHg obtuvieron disminuciones significativas de presión intraocular tras el ejercicio ($p \leq 0.001$ en todos los casos, tamaños del efecto entre 0.57 y 1.02). En cambio, las mujeres, los sujetos menores de 25 años y los sujetos con niveles de presión intraocular de reposo iguales o por debajo de 14 mmHg no mostraron variaciones significativas de presión intraocular tras el ejercicio (valores de significancia [*p*] entre 0.114 y 0.312). Se observaron diferencias significativas en las variaciones de presión intraocular entre los sujetos con presión intraocular de reposo por debajo o iguales a 14 mmHg y los sujetos con presión intraocular igual o mayor de 17 mmHg ($p = 0.008$, tamaño del efecto: 0.96).

Estos resultados confirman que el comportamiento de la presión intraocular tras el ejercicio es multifactorial. Los profesionales que trabajen con personas con riesgo de padecer presión intraocular elevada deberían tener en cuenta diferencias individuales como el sexo, la edad y los niveles basales de presión intraocular para programar entrenamientos acordes a la situación de cada sujeto.

Segundo estudio: Caracterización de las variantes de sentadilla más comunes

El segundo artículo del compendio, incluido en el **Capítulo 3**, recoge una caracterización de la información biomecánica, kinesiológica, y mioeléctrica de las variaciones de sentadilla más comunes (es decir, sentadilla trasera barra alta, sentadilla trasera barra baja, sentadilla frontal, sentadilla con barra por encima de la cabeza y sentadilla guiada). El objetivo de este estudio fue obtener información de la literatura científica para seleccionar la variante de sentadilla más adecuada y ser esta incluida como referencia en las siguientes investigaciones de la presente tesis doctoral.

Para lograrlo, se llevó a cabo una revisión sistemática en cuatro bases de datos y diferentes búsquedas manuales. Tras pasar los filtros basados en los criterios de selección de artículos se recopilaron 30 artículos. La calidad de los estudios incluidos se evaluó mediante la escala PEDro, obteniendo todos ellos una puntuación de entre 5 y 6 sobre un máximo de 6 puntos. Las variantes de sentadillas escogidas fueron la sentadilla trasera con barra alta (26 artículos la analizaban), sentadilla trasera con barra baja (un artículo la analizaba), sentadilla frontal (cinco artículos la analizaban), sentadilla con barra por encima de la cabeza (dos artículos la analizaban) y sentadilla trasera con barra alta realizada en máquina Smith (dos artículos la analizaban). Se incluyeron el glúteo mayor, glúteo medio, aductores, vasto lateral, vasto medial, recto femoral, bíceps femoral, semitendinoso, tibial anterior, gastrocnemio y sóleo, como musculatura que actúa sobre las caderas, rodillas y tobillos.

La ejecución de la sentadilla, común a todas las variantes, inicia con el participante en posición de bipedestación. Se realiza una flexión sinergista de cadera, rodilla y tobillo en el descenso, seguida de una extensión en el ascenso, para terminar con el participante en la posición inicial. Los resultados de la presente revisión, a nivel general, mostraron que la sentadilla es un ejercicio en el que se activa predominantemente la musculatura extensora de la rodilla, es decir principalmente los músculos del cuádriceps (vasto lateral, vasto medial, recto femoral y vasto intermedio). A pesar de esto anterior, modificaciones en la posición de la barra pueden aumentar la actividad de la musculatura extensora de la cadera, como por ejemplo en la sentadilla trasera con barra baja. La mayoría de las investigaciones examinadas

(26 artículos) analizaron la sentadilla trasera con barra alta, con resultados relativamente homogéneos en cuanto a los patrones de activación. La carga fue identificada como el mayor determinante de los niveles de activación muscular. Además, se observó que diferentes modificaciones técnicas (profundidad del movimiento, separación de los pies, rotación de las caderas, orientación de las puntas de los pies) conllevaban diferentes patrones de activación muscular.

Tras todos los análisis realizados, la sentadilla trasera con barra alta y realizada en máquina Smith fue seleccionada para ser incluida en la metodología de los otros dos estudios sobre sentadillas de esta tesis. Respecto a la ejecución técnica, se escogió una profundidad de sentadilla hasta la paralela del fémur con el suelo y posiciones neutras en cuanto a separación de pies, rotación de caderas y orientación de las puntas de los pies.

Tercer estudio: El potencial de las bandas elásticas para maximizar el rendimiento en sentadillas

El tercer artículo del compendio, presentado en el **Capítulo 3**, pone a prueba un nuevo método de cargar la barra con bandas elásticas en sentadillas. El peso pertinente que cada participante debía movilizar en función del porcentaje de la repetición máxima fue añadido a la barra utilizando exclusivamente bandas elásticas en la posición de bipedestación o justo por encima del punto de estancamiento (*sticking point*) de la rodilla de cada participante.

Veinte hombres sanos y físicamente activos, con al menos un año de experiencia en el entrenamiento de la fuerza (edad: 25.50 ± 5.26 años; índice de masa corporal: 24.09 ± 2.06 kg/m^2; grasa corporal: 10.16 ± 2.23%; kilogramos para una repetición máxima en sentadilla: 127.10 ± 24.10 kg; ratio kilogramos para una repetición máxima por peso corporal [fuerza relativa]: 1.70 ± 0.36), participaron en tres sesiones: dos para evaluación y familiarización y una experimental. En la sesión experimental, se realizaron seis series (tres utilizando exclusivamente discos para cargar la barra y tres utilizando sólo bandas elásticas) de sentadillas en orden aleatorio. Cuatro series (dos con discos y dos bandas elásticas) fueron realizadas hasta el fallo muscular y dos series (una con discos y una con bandas elásticas) consistieron en esfuerzos submáximos. La altura a la que se encontraba la barra en el punto de estancamiento de cada participante se marcó tras medir el punto mediante goniometría en la articulación de la rodilla. En la condición correspondiente, las bandas elásticas se aplicaron con el peso pertinente justo por encima de este punto. Inmediatamente al terminar cada serie, se midieron los kilogramos utilizados en bipedestación, el número de repeticiones realizadas, frecuencia cardíaca, presión arterial y ratio de esfuerzo percibido. Se llevaron a cabo un análisis de la varianza de medidas repetidas de una vía con ajustes de Bonferroni y pruebas no paramétricas de Friedman y Wilcoxon para evaluar diferencias en las variables de estudio entre las distintas condiciones de sentadilla. El nivel de significancia fue uniformemente establecido en $p < 0.05$.

Cuando el peso era equiparado entre discos y bandas elásticas en posición de bipedestación, las bandas elásticas permitieron realizar alrededor de ocho repeticiones más ($p < 0.001$; tamaño del efecto: 2.44) con los mismos kilogramos en posición de bipedestación (menos en fases más profundas), con respuestas de carga interna similares (presión arterial, ratio de esfuerzo percibido) en comparación con los discos. En cambio, cuando las bandas elásticas se aplicaron justo por encima del punto de estancamiento, estas permitieron realizar alrededor de tres repeticiones más ($p = 0.001$, tamaño del efecto: 1.27) con aproximadamente 25% más kilogramos ($p = 0.001$, tamaño del efecto: 1.15) en la posición de bipedestación (mismo peso en el punto de estancamiento y menos peso por debajo del mismo) y con respuestas similares de presión arterial y frecuencia cardíaca ($p > 0.05$).

Estos resultados confirman que las bandas elásticas pueden ser un material óptimo para cargar la barra en entrenamientos de la fuerza en el ejercicio de sentadilla en hombres jóvenes entrenados. Además, sugieren que la aplicación justo por encima del punto de estancamiento podría ser una metodología útil para aumentar el rendimiento mediante la superación de la fase del movimiento más biomecánicamente desventajosa de la sentadilla, en la que se suele perder la técnica y tener lugar el fallo. Los hallazgos de este estudio permiten establecer la base para futuras investigaciones utilizando bandas elásticas para mejorar el rendimiento en el ejercicio físico. Entre otras futuras líneas de investigación, estudios de intervención a medio o largo plazo deberían evaluar el potencial del estímulo de entrenamiento proporcionado por aplicar las bandas elásticas justo por encima del punto de estancamiento en sentadilla y/o otros ejercicios para producir adaptaciones crónicas. También, sería interesante evaluar si se obtiene el mismo incremento en el peso y número de repeticiones cuando se añade un 25% más de la carga directamente en la posición de bipedestación en comparación con la metodología de cargar la barra justo por encima del punto de estancamiento.

Cuarto estudio: Las bandas elásticas como material para provocar respuestas oculares y cardiovasculares conservadoras

Basándose en los resultados de los Capítulos 2, 3 y 4, el cuarto y último artículo publicado en el compendio, descrito y desarrollado en el **Capítulo 5**, analizó las posibles respuestas oculares y cardiovasculares tras realizar sentadillas utilizando bandas elásticas para cargar la barra. Además, se evaluó si estas respuestas fisiológicas eran similares en comparación a las respuestas obtenidas al realizar sentadillas con discos. El objetivo principal de esta investigación fue examinar las respuestas oculares (presión intraocular, presión de perfusión ocular y espesor corneal central) y cardiovasculares (presión arterial media, presión del pulso y frecuencia cardíaca) producidas por realizar sentadillas con discos o bandas elásticas y comparar las respuestas tras un carácter del esfuerzo máximo y submáximo.

Veinte hombres sanos y físicamente activos, con al menos un año de experiencia en el entrenamiento de la fuerza, participaron de forma voluntaria en el estudio (edad: 25.55 ± 4.75 años; masa corporal: 75.67 ± 9.02 kg; índice de masa corporal: 24.04 ± 2.11 kg/m^2; grasa corporal: 10.19 ± 2.29 %; kilogramos para una repetición máxima en sentadilla: 126.53 ± 24.62 kg; ratio kilogramos para una repetición máxima por peso corporal [fuerza relativa]: 1.68 ± 0.35). Se llevaron a cabo dos sesiones, una de evaluación y familiarización y una experimental. En la sesión experimental se realizaron repeticiones hasta el fallo y repeticiones submáximas con un 75% de una repetición máxima con bandas elásticas (cargadas en la posición de bipedestación) o con discos. Es decir, se realizaron un total de cuatro series diferentes (dos con discos y dos con bandas elásticas). Se tomaron medidas pre-ejercicio de cada uno de los parámetros cardiovasculares y oculares. Posteriormente, tras un calentamiento estandarizado, se realizó cada una de las series en orden aleatorio. Las mediciones cardiovasculares se realizaron inmediatamente al terminar cada serie. Las mediciones oculares se iniciaron uniformemente un minuto después de terminar cada serie. Un análisis de la varianza de medidas repetidas de dos vías con el material y el carácter del esfuerzo como factores intra-sujeto evaluó diferencias entre las diferentes condiciones de sentadilla realizadas. Además, un análisis de la varianza de medidas repetidas de una vía evaluó diferencias entre los valores pre-ejercicio y los valores obtenidos tras cada una de las condiciones experimentales. Se estableció un nivel de significancia en $p < 0.05$.

Las bandas elásticas permitieron realizar más repeticiones con los mismos kilogramos en bipedestación (menos en las partes más profundas de la sentadilla). A nivel de los parámetros fisiológicos analizados relacionados con esta tesis, la presión intraocular fue significativamente más baja que antes del ejercicio (tamaños del efecto entre 0.73 y 1.00). De la misma manera, la presión de perfusión ocular media (tamaños del efecto entre 1.14 y 1.36), la frecuencia cardíaca (tamaños del efecto entre 2.42 y 2.77), la presión del pulso (tamaños del efecto entre 0.80 y 1.32) y la presión arterial media (tamaños del efecto entre 0.85 y 1.16) fueron significativamente más altas en comparación con los valores pre-ejercicio. En cambio, el espesor corneal central no varió significativamente ($p = 0.828$). Se encontraron respuestas cardiovasculares y oculares similares ($p > 0.05$) entre el uso de los discos (menos repeticiones, más kilogramos de media) y las bandas elásticas (más repeticiones, menos kilogramos de media). Aunque no se observó un efecto significativo del material sobre los parámetros oculares ($p > 0.05$), el mayor descenso de presión intraocular (2.70 mmHg) se encontró tras realizar el máximo número de repeticiones con bandas elásticas; se observó una tendencia a diferencias estadísticamente significativas comparando con el máximo número de repeticiones con discos (diferencia media: 0.55 mmHg, intervalo de confianza al 95% [-0.12–1.22]; p = 0.10; tamaño del efecto: 0.21). Por tanto, las bandas elásticas parecen un dispositivo apropiado para cargar la barra en sentadillas para sujetos que deberían evitar incrementos de presión intraocular.

Para complementar estos resultados, futuros estudios deberían comparar las variaciones de presión intraocular obtenidas a lo largo de todo el rango de movimiento con el uso de discos o de bandas elásticas para cargar la barra, diferenciando entre las fases del movimiento, por ejemplo, concéntrica y excéntrica. Además, se deberían evaluar las adaptaciones crónicas de presión intraocular y presión de perfusión ocular obtenidas con entrenamiento de la fuerza con bandas elásticas en sujetos sanos, sujetos mayores, sujetos en riesgo de sufrir glaucoma y sujetos con glaucoma diagnosticado.

Los hallazgos de la presente investigación sugieren que la cantidad de trabajo total (repeticiones x peso) podría condicionar las respuestas oculares y cardiovasculares. Con el objetivo de mantener respuestas de presión intraocular conservadoras, a nivel general, se podría recomendar el control de la técnica, tempo de movimiento y evitar la maniobra de Valsalva. Siguiendo estos términos, los discos y las bandas elásticas podrían ser utilizados de manera indistinta en lo que a respuestas oculares y cardiovasculares se refiere. Los optometristas, oftalmólogos y/o profesionales del ejercicio físico trabajando con personas en riesgo de padecer presión intraocular elevada, u otros factores asociados al desarrollo del glaucoma, podrían encontrar de utilidad los hallazgos del presente estudio.

Conclusiones

Los hallazgos de la presente tesis doctoral, mostrados a través de los resultados de los cuatro artículos desarrollados, establecen una base para investigaciones futuras con bandas elásticas desde una perspectiva de rendimiento. De la misma manera, los resultados obtenidos en cuanto a parámetros de salud ocular y cardiovascular abren nuevas vías para comprender factores externos (variables de programación de entrenamiento) e internos (sociodemográficos y fisiológicos) que potencialmente condicionan las adaptaciones fisiológicas agudas al ejercicio.

Las principales conclusiones a destacar y que responden a las tres hipótesis de la presente tesis doctoral se presentan a continuación. En primer lugar, la presión intraocular medida tras realizar una sesión de gimnasia acrobática es menor que antes del ejercicio, obteniéndose diferencias significativas entre sexos, grupos de edad y grupos formados según niveles de presión intraocular de reposo. Los niveles de presión intraocular en reposo y el sexo aparecieron como predictores significativos de las variaciones de presión intraocular debidas al ejercicio. Segundo, las bandas elásticas, cuando se cargan a la barra justo por encima del punto de estancamiento con el peso correspondiente, permiten utilizar un 25% más de peso en posición de bipedestación y hacer aproximadamente tres repeticiones más que el mismo porcentaje de una repetición máxima con discos, sin diferencias significativas en la presión arterial y frecuencia cardíaca. Tercero, la presión intraocular medida tras realizar sentadillas es significativamente menor que antes del ejercicio y la presión de perfusión ocular media, presión del pulso y presión arterial media más elevada, sin diferencias significativas entre el uso de bandas elásticas o discos para cargar la barra.

Además de arrojar cierta luz sobre el uso potencial de las bandas elásticas y sus diferentes aplicaciones para maximizar el rendimiento, el compendio de artículos que compone la presente tesis doctoral contribuye a la colaboración multidisciplinar entre profesionales del entrenamiento de la fuerza y el acondicionamiento físico, optometristas y oftalmólogos para concienciar en la importancia de la prevención, manejo y control de factores de riesgo asociados al glaucoma como fluctuaciones de presión intraocular, presión de perfusión ocular y presión arterial.

Contents

Symbols and abbreviations

- Δ%: Percentage of variation.
- α: Type 1 error.
- ß: Type 2 error.
- d_{unb}: Cohen's *d* as a measure of the effect size in two-group comparisons.
- ε: Non-sphericity correction.
- f^2: Cohen's f as a measure of the effect size in linear regression.
- f(V): Cohen's f as a measure of the effect size in analysis of variance.
- ηp^2: Eta partial squared as a measure of the effect size.
- *p*: *p*-value of significance.
- ANOVA: Analysis of variance.
- F: Analysis of variance statistic.
- Max75%1RMEB: Maximum number of repetitions at 75% of one-repetition maximum with elastic bands.
- Max75%1RMWP: Maximum number of repetitions at 75% of one-repetition maximum with weight plates.
- mmHg: Millimeters of mercury as a measure of pressure.
- MLR: Multiple linear regression.
- OMNI-RES: Omnibus Resistance Exercise Scale.
- PEDro: Physiotherapy Evidence Database.
- PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis.
- REB: Repetitions with elastic bands.
- RM: Repetition maximum.
- RMWP: Repetition maximum with weight plates.
- RSMWP: Submaximal repetitions with weight plates.
- Submax75%1RMEB: Submaximal repetitions at 75% of one-repetition maximum with elastic bands.
- Submax75%1RMWP: Submaximal repetitions at 75% of one-repetition maximum with weight plates.
- XRMEB: Maximum number of repetitions with elastic bands.
- XRMEBSP: Maximum number of repetitions with elastic bands with the pertinent weight added just above the sticking point.

Table list

Figure list

Regulation and structure

According to the regulations approved by the Doctoral School and the Academic Committee of the PhD Program in Physiology of the University of Valencia, the present doctoral thesis has been structured in the form of a compendium of four publications:

1. **Gene-Morales, J.**, Gené-Sampedro, A., Martín-Portugués, A., & Bueno-Gimeno, I. (2021). Do age and sex play a role in the intraocular pressure changes after acrobatic gymnastics? *Journal of Clinical Medicine, 10*(20), 4700.
2. **Gene-Morales, J.**, Flandez, J., Juesas, A., Gargallo, P., Miñana, I., & Colado, J. C. (2020). A systematic review on the muscular activation on the lower limbs with five different variations of the squat exercise. *Journal of Human Sport and Exercise*, *15*(Proc4), S1277–S1299.
3. **Gene-Morales, J.**, Gené-Sampedro, A., Salvador, R., & Colado, J. C. (2020). Adding the load just above the sticking point using elastic bands optimizes squat performance, perceived effort rate, and cardiovascular responses. *Journal of Sports Science & Medicine*, *19*(4), 735–744.
4. **Gene-Morales, J.**, Gené-Sampedro, A., Salvador, R., & Colado, J. C. (2022). Effects of squatting with elastic bands or conventional resistance-training equipment at different effort levels in the post-exercise intraocular pressure of healthy men. *Biology of Sport*, *39*(4), 895–903.

The indexation of the journals in which the articles of the compendium have been published and other scientific articles and actions for scientific outreach that justify and underpin the present doctoral thesis are presented in Chapter 9.

Chapter 1. Introduction

1. Introduction

Physical exercise and more specifically resistance training are associated with improvements in athletic performance (González-Badillo et al., 2014; Harries et al., 2012; Izquierdo et al., 2006; Kraemer & Ratamess, 2004; Wernbom et al., 2007) and uncountable benefits related to health (e.g., improvement of insulin resistance, resting metabolic rate, glucose metabolism, blood pressure, body fat levels, gastrointestinal transit, reduction of back pain and discomfort associated with arthritis and fibromyalgia, and reduction of all-cause and cancer mortality, among others; Fritz et al., 2021; Stamatakis et al., 2018; Westcott, 2012; Winett & Carpinelli, 2001). To maximize these potential benefits of resistance training, manipulation of programming variables (e.g., exercise selection, intensity, volume, type of material) is required (Garber et al., 2011; Halson, 2014; Kraemer & Ratamess, 2004; Wernbom et al., 2007).

Concerning exercise selection, the squat is one of the most commonly used exercises for health and performance purposes due to its biomechanical and neuromuscular similarities with a wide range of everyday activities and athletic movements (V. Andersen et al., 2016; Clark et al., 2012; Kompf & Arandjelović, 2017; Schoenfeld, 2010b). The squat movement involves synergistic hip, knee, and ankle flexion in the descent followed by knee and hip extension in the ascent and finishes with the individual in the standing position (Clark et al., 2012; Escamilla et al., 2001; Iversen et al., 2017; Schoenfeld, 2010b; Vigotsky et al., 2019). However, squats can be performed in different ways (modifying the descent depth, stance width, orientation of the knee flexion planes, bar placement, and materials used to load the bar) with significant biomechanical and neuromuscular differences between them (Clark et al., 2012; Gene-Morales, Flandez, et al., 2020; Kompf & Arandjelović, 2017; Schoenfeld, 2010b; Van den Tillaar et al., 2014), as similarly shown for deadlifts in a study related to the present doctoral thesis project (Flandez, Gene-Morales, Juesas, et al., 2020). Regarding bar placement, the most common squat variations are the high-bar back squat, low-bar back squat, front squat, overhead squat, and other less common variations such as the Zercher squat (Bautista, 2019). These main variations are further discussed in Chapter 3, emphasizing the differences in muscle activation between selected stance and depth.

Concerning the material used to load the bar, the use of elastic bands in combination with free weights to load the bar in squats has previously been studied (V. Andersen et al., 2015, 2016; Ebben & Jensen, 2002; Iversen et al., 2017; Joy et al., 2016; Saeterbakken et al., 2014, 2016). The specific characteristics of elastic bands as variable resistance equipment for resistance training are addressed in the following section.

1.1 A biomechanical approach to the use of elastic bands to load the bar in squats for performance optimization

The use of elastic bands for resistance training is increasing in popularity due to the positive health and physical performance outcomes obtained in several studies (Colado et al., 2010; Colado, Mena, et al., 2020; Colado & Triplett, 2008; Saeterbakken et al., 2014, 2016; Soria-Gila et al., 2015), including two conducted in line with this doctoral thesis research (Flandez, Gene-Morales, Modena, et al., 2020; Hammami et al., 2021).

The main feature of elastic bands, which is known as the elongation coefficient, is that the resistance (the kilograms) provided increase with increasing band length and decrease with decreasing band length regardless of gravity (V. Andersen et al., 2016; Frost et al., 2010; Saeterbakken et al., 2016). Applying this principle to the squat movement results in a reduction of the kilograms provided by the elastic bands during the descent (eccentric phase) and an increase during the ascent (concentric phase). This reduction in the kilograms provided by the elastic bands during the deepest phases of the squat movement has been an issue to obtain the desired weight in previous research (Saeterbakken et al., 2016), and this fact could decrease muscle activation (Iversen et al., 2017).

Different strategies have been proposed to increase the weight provided by the elastic bands during resistance training exercises, such as increasing the number of bands (Page et al., 1993) or increasing the initial tension of the band, either augmenting the distance from the handle to the attachment (Page et al., 2015; Treiber et al., 1998) or shortening the initial length of the band (Aboodarda et al., 2013). Through these uses of elastic bands, authors obtained similar or even higher muscle activation levels (Aboodarda et al., 2013), improvements in functional performance for sports (Page et al., 2015; Treiber et al., 1998), and further strength gains (Treiber et al., 1998) compared to constant resistance. However, these strategies do not consider the variability in participants' characteristics such as height or execution form and could therefore present limited opportunities for the squat exercise (Iversen et al., 2017). Bearing this issue in mind, the question arises whether adding the specific load at different points of the range of motion depending on the subject characteristics could optimize the weight used and the performance. For the purpose of optimizing the weight used throughout the range of motion, the terms "sticking region" and "sticking point" are presented.

1.1.1 The sticking region and sticking point

The sticking region is defined as the part of the range of motion in which a disproportionally large increase in difficulty occurs due to mechanical constraints (Kompf & Arandjelović, 2016, 2017). This leads to a decrease in the upward velocity of the barbell (Saeterbakken et al., 2016; Van den Tillaar et al., 2014) and an increase in the chances of exercise form breakdown (Kompf & Arandjelović, 2016; Schoenfeld, 2010b; Vigotsky et al., 2019). In the poststicking region, velocity increases again due to more favorable biomechanical conditions (V. Andersen et al., 2016; Saeterbakken et al., 2016; Van den Tillaar et al., 2014).

A sticking region has been observed in numerous exercises but was first identified and studied in the squat (Kompf & Arandjelović, 2017). To locate where this sticking region ends (sticking point) in the squat, different biomechanical parameters are used such as the thigh angle relative to the ground (Kompf & Arandjelović, 2017); knee flexion degrees (Escamilla et al., 2001); and hip, knee, or even ankle joint degrees (Hales et al., 2009; Van den Tillaar et al., 2014). Focusing on the knee joint angle formed by the tibia and femur (standing position at 180º), angles of approximately 101º (Hales et al., 2009), 102º (Van den Tillaar et al., 2014), and 121º (Escamilla et al., 2001) appear in the scientific literature, with the average being approximately 108º.

Numerous strategies have been proposed to overcome the biomechanically disadvantageous sticking region such as forced repetitions, drop sets (Schoenfeld, 2011), accommodation, and use of variable resistance such as elastic bands or chains (Kompf & Arandjelović, 2016). Considering the elongation coefficient, elastic bands provide less weight during the more mechanically disadvantageous region of the range of motion (i.e., below the knee sticking point at lower knee angles) and more weight with increasing knee angles (V. Andersen et al., 2016; Iversen et al., 2017; Joy et al., 2016; Kompf & Arandjelović, 2016). Therefore, when trying to maximize the weight provided by elastic bands, the question arises whether the pertinent weight (the same as those used with weight plates) could be added exclusively using elastic bands to load the bar immediately above the sticking point in a squat. In this way, participants would use the same weight as with weight plates at the sticking point, less weight in the mechanically disadvantageous deepest phases of the squat (sticking region), and more weight in the more mechanically efficient parts of the range of motion (poststicking region; see Figure 1). Furthermore, the weight reduction during the deepest phases of the squat would be minor compared to the pertinent weight being added with elastic bands at the standing position. This individual-based approach may reduce the differences or even equate the mean weight used with elastic bands or weight plates, with elastic bands adding optimal resistance throughout the range of motion and therefore potentially maximizing the performance (Iversen et al., 2017).

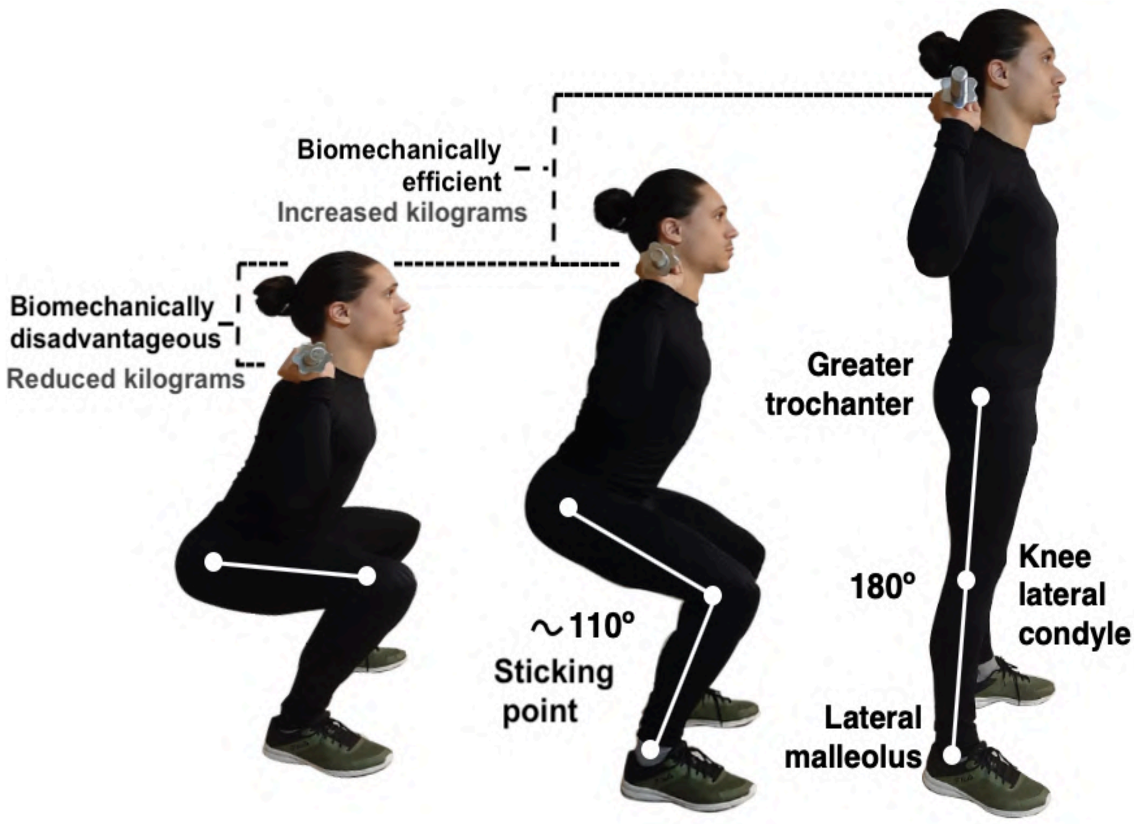

Figure 1. Depiction of the sticking region (biomechanically disadvantageous), poststicking region (biomechanically efficient), and distribution of the weight in a squat movement using elastic bands to load the bar.

1.1.2 Parameters used to analyze the performance

Performance can be monitored in different ways. A squat program periodization is often measured by the external and internal load (Halson, 2014). The number of repetitions performed and kilograms employed are some of the specific variables commonly used to quantify the external load, while different physiological and perceptual variables are used to quantify the internal load (Halson, 2014). The most popular methods to determine training weights are repetitions maximum (RM) or percentage of one-repetition maximum (1RM), with 1RM being the maximum kilograms a participant can lift in one repetition (Aboodarda et al., 2013; Bryanton et al., 2012; Reynolds et al., 2006). Percentages of 1RM between 70 and 85% are commonly employed in resistance training programs (Kraemer et al., 2002; Schoenfeld, 2011). Concerning the internal load, heart rate, blood pressure, and subjective scales of the rate of perceived exertion are recognized as an adequate reflection of the physiological and physical performance responses with both weight plates and elastic bands (Colado et al., 2010, 2012; Colado & Triplett, 2008; Halson, 2014; Iglesias-Soler et al., 2015; Maté-Muñoz et al., 2015; Robertson et al., 2003).

Apart from all the potential enhancements that elastic bands could entail for the squat performance, the reduction in the weight provided by elastic bands in the deepest phases of the range of motion could also provide health benefits. The potential usefulness of elastic bands for a health approach, and more specifically for cardiovascular and ocular health, is discussed in the following section.

1.2 The potential use of elastic bands to load the bar in squats for health purposes

As previously mentioned, resistance training is associated with numerous positive effects for health (Stamatakis et al., 2018; Westcott, 2012; Winett & Carpinelli, 2001). However, the benefits of resistance training should be understood as a multifactorial process. Resistance training should be individually prescribed since it may involve certain risks (Warburton & Bredin, 2016). For instance, although resistance training reduces the blood pressure in the hours following the exercise and in the long term (Carpio-Rivera et al., 2016; Cornelissen et al., 2011), the high intramuscular pressure produced by strong muscle contractions mechanically compresses local blood vessels and acutely increases blood pressure (Castinheiras-Neto, 2010; Gjovaag et al., 2016; Iglesias-Soler et al., 2015), which can increase the risk of cardiovascular events (Cornelissen et al., 2011; Franklin et al., 1999; Neto et al., 2017). Similarly, the use of heavy loads during resistance training may cause an abrupt increase in intraocular pressure (Rüfer et al., 2014; Vera, García-Ramos, et al., 2017; Vera, Jiménez, Redondo, Torrejón, et al., 2018; Vera, Jiménez, Redondo, Torrejón, De Moraes, et al., 2019; Vera, Perez-Castilla, et al., 2019; Vera et al., 2020; Vieira et al., 2006), although one study showed reductions in the long term (Ibrahim & Elbeltagi, 2019). These increments in intraocular pressure may be detrimental for ocular health and be a risk factor for the development and progression of primary open-angle glaucoma, a neurodegenerative eye pathology and a leading cause of irreversible blindness worldwide (Guo et al., 2019; J. H. Kim & Caprioli, 2018).

Due to all the aforementioned factors regarding ocular and cardiovascular health, understanding the effects that resistance training may have on the ocular and cardiovascular systems is crucial to preserving health. In this regard, while the effect of resistance training on the cardiovascular system has been more widely studied, controversy exists concerning the effects of resistance training on certain ocular parameters such as intraocular pressure. Furthermore, to the best of our knowledge, cardiovascular and ocular acute adaptations to the use of elastic bands to load the bar in squats remain unstudied. Hereafter, common conditions related to ocular (primary open-angle glaucoma) and cardiovascular health (hypertension) are briefly described. Additionally, the potential usefulness of elastic bands as a device to load the bar for squatting and their specific acute influence in the cardiovascular and ocular systems are presented.

1.2.1 Ocular health

Primary open-angle glaucoma is the second cause of irreversible blindness worldwide after cataracts (Allison et al., 2020; Dietze et al., 2021; Guo et al., 2019; J. H. Kim & Caprioli, 2018; Sreenivas et al., 2018), with a global prevalence of approximately 2.2% (Allison et al., 2020; Weinreb et al., 2016). This neurodegenerative disease is clinically characterized by observable structural changes in the optic nerve head and retinal nerve fiber layer (i.e., degeneration of retinal ganglion cells and their axons) associated with visual field loss (Allison et al., 2020; Knepper & Samples, 2020; Samples & Knepper, 2018; Weinreb et al., 2016).

The exact pathophysiological mechanisms of optic nerve damage in primary open-angle glaucoma are complex and not fully understood (Agarwal et al., 2009; Sreenivas et al., 2018). Although this condition can occur at any eye pressure, ocular hypertension and intraocular pressure fluctuations can cause biomechanical deformation of the optic nerve head (the predominant site of damage), which may adversely affect retinal ganglion cell function, including the transport of crucial neurotrophic factors (Agarwal et al., 2009; J. H. Kim & Caprioli, 2018; Weinreb et al., 2016). Figure 2 presents the optic nerve head injury in glaucoma, which leads to retinal ganglion cell damage and death through multiple mechanisms such as reactive gliosis and remodeling of the extracellular matrix at the lamina cribrosa, reduced axonal transport of neurotrophins and mitochondria, and reduced blood flow to the eye (Agarwal et al., 2009; Weinreb et al., 2016). The visual field defects in glaucomatous eyes are often detected after 40% of the axons are lost (Agarwal et al., 2009). Retinal ganglion cell survival is potentially influenced by genetic predisposition and other mechanisms such as neurotrophic support, excitotoxicity, or autoimmune mechanisms within the retina (Weinreb et al., 2014, 2016). Furthermore, Figure 2 presents the responses to retinal ganglion cell damage, including cellular mechanisms that result in the breakdown of retinal ganglion cell somas (by apoptosis) or axons (by Wallerian degeneration) or adaptative responses (such as dendritic remodeling) to maintain function in surviving cells (Weinreb et al., 2016).

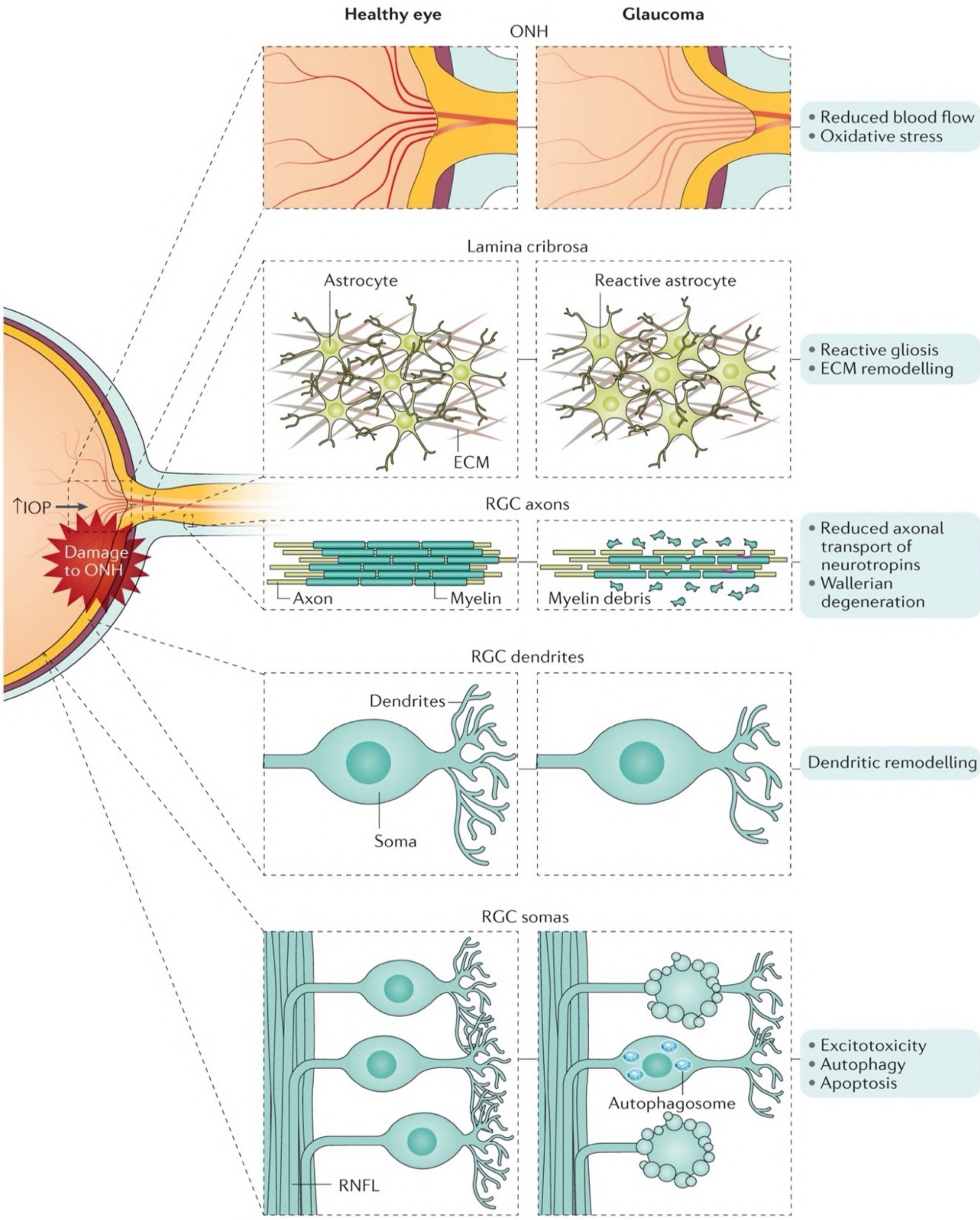

Figure 2. Retinal ganglion cell injury and response in glaucoma. IOP: intraocular pressure. ONH: optic nerve head. ECM: extracellular matrix. RGC: retinal ganglion cell. RNFL: retinal nerve fiber layer. Retrieved from: Weinreb, R. N., Leung, C. K. S., Crowston, J. G., Medeiros, F. A., Friedman, D. S., Wiggs, J. L., & Martin, K. R. (2016). Primary open-angle glaucoma. *Nature Reviews Disease Primers, 2*(1), 16067.

Primary open-angle glaucoma depends on a combination of vascular, genetic, anatomical, and immune factors (Agarwal et al., 2009; Allison et al., 2020; Weinreb et al., 2016). Existing treatments for primary open-angle glaucoma are designed to lower intraocular pressure, which is a major risk factor for optic nerve damage (Y. W. Kim & Park, 2019; Knepper et al., 2020; Samples & Knepper, 2018). Additionally, reduced optic nerve head blood flow can cause ischemic insults to unmyelinated retinal ganglion cell axons at the lamina cribrosa of the optic nerve head (Deb et al., 2014; Parekh et al., 2018; Topouzis & Panayiota, 2009; Trivli et al., 2019; Weinreb et al., 2016). In summary, the stability of the optic nerve tissues highly depends on the blood supply through the ocular microcirculation, which is conditioned by the intraocular pressure and ocular perfusion pressure (Deb et al., 2014; Guo et al., 2019; J. H. Kim & Caprioli, 2018; McMonnies, 2016; Wylęgała, 2016). These two terms (intraocular pressure and ocular perfusion pressure) and their importance to ocular health are defined in the following sections. The role of central corneal thickness in ocular health is also presented.

Intraocular pressure

Intraocular pressure is defined as the force exerted by the aqueous humor on the internal surface area of the anterior chamber of the eye, namely from the posterior cornea to the anterior lens (Machiele et al., 2021; Weinreb et al., 2014). Aqueous humor is produced in the ciliary bodies to supply oxygen and glucose to the avascular lens and cornea, and it is drained through the trabecular meshwork and uveoscleral outflow pathway as Figure 3 shows (Weinreb et al., 2016). Intraocular pressure levels (measured in mmHg) are determined by an equilibrium between aqueous humor production and outflow (Machiele et al., 2021; Murgatroyd & Bembridge, 2008; Weinreb et al., 2014, 2016). The normal physiological range of intraocular pressure has been established between 10 and 21 mmHg (Weinreb et al., 2016).

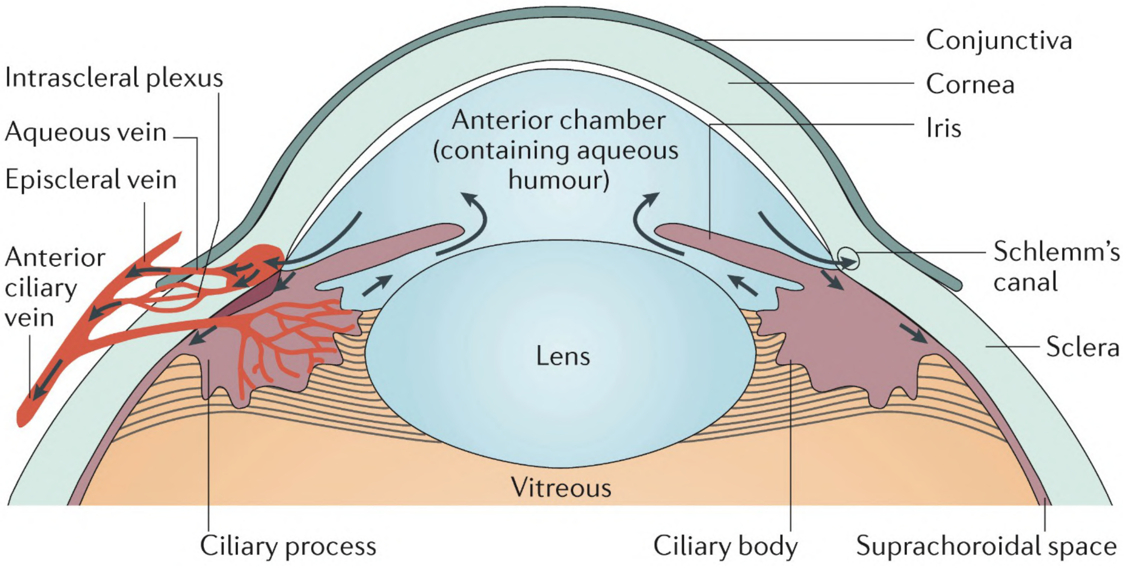

Figure 3. Aqueous humor production and outflow in the eye. Retrieved from: Weinreb, R. N., Leung, C. K. S., Crowston, J. G., Medeiros, F. A., Friedman, D. S., Wiggs, J. L., & Martin, K. R. (2016). Primary open-angle glaucoma. *Nature Reviews Disease Primers, 2*(1), 16067.

Physiological intraocular pressure variations occur in regular rhythmic cycles, and compensatory mechanisms preserve tissue stability (Guo et al., 2019; Machiele et al., 2021). Irregular nonphysiological elevations and fluctuations may disrupt these homeostatic mechanisms (J. H. Kim & Caprioli, 2018). When these compensatory mechanisms fail, mechanical compression of the optic nerve fiber bundles and a consequent discontinuity of axonal transport may occur (Guo et al., 2019). In addition, if intraocular pressure values are higher than the ocular perfusion pressure, a restriction of blood supply to the optic nerve occurs (see Figure 4), which may lead to ischemia-reperfusion tissue damage (Machiele et al., 2021; Zhu et al., 2018). The term "ocular perfusion pressure" refers to the difference between blood pressure and intraocular pressure and represents the blood flow to the eye (Trivli et al., 2019; Van Keer et al., 2016), as is developed in the following section. Additionally, corneal thickness has been identified as playing a role in short-term intraocular pressure fluctuations (T. T. Wong et al., 2009).

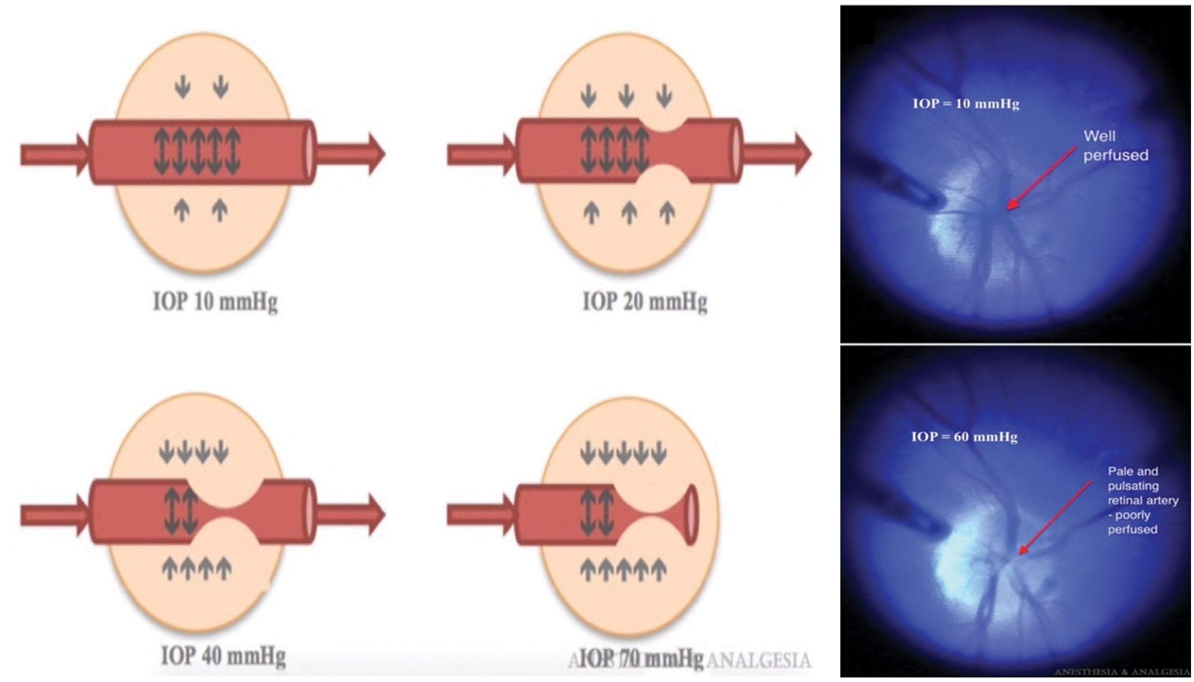

Figure 4. The role of intraocular pressure in determining ocular blood flow. Adapted from: Kelly, D. J. & Farrell, S. M. (2018). Physiology and role of intraocular pressure in contemporary anesthesia. *Anesthesia & Analgesia, 126*(5), 1551-1562.

Intraocular pressure can fluctuate due to different internal and external factors. Among these, age and sex are acknowledged factors that condition intraocular pressure (McMonnies, 2016; Wylęgała, 2016). Additionally, central corneal thickness (T. T. Wong et al., 2009) and baseline intraocular pressure levels (Caprioli & Coleman, 2008; J. H. Kim & Caprioli, 2018) have been identified as playing a role in short-term intraocular pressure fluctuations. Exercise is a key external factor that modifies intraocular pressure (Y. W. Kim & Park, 2019; McMonnies, 2016; Tribble et al., 2021; Wylęgała, 2016; Zhu et al., 2018). Therefore, the question arises whether sociodemographic and ocular variables such as sex, age, baseline intraocular pressure, and baseline central corneal thickness could play a role and predict the intraocular pressure variations provoked by exercise.

Regarding the exercise methodology, continuous aerobic exercise such as running or cycling at low to moderate intensities has proven to acutely reduce intraocular pressure (Roddy et al., 2014; Vera et al., 2021; Yuan et al., 2021; Zhu et al., 2018). On the other hand, controversial results appear in the scientific literature concerning dynamic resistance training involving muscular strength such as weightlifting, with many studies ensuring intraocular pressure elevations (Rüfer et al., 2014; Song et al., 2009; Vaghefi et al., 2021; Vera, García-Ramos, et al., 2017; Vera, Jiménez, Redondo, Cárdenas, et al., 2018; Vera, Jiménez, Redondo, Torrejón, et al., 2018; Vera, Jiménez, Redondo, Torrejón, De Moraes, et al., 2019; Vera, Perez-

Castilla, et al., 2019; Vera et al., 2020; Vieira et al., 2006) and others reporting reductions due to the exercise effect (Avunduk et al., 1999; Chromiak et al., 2003; Conte et al., 2009, 2012; Conte & Scarpi, 2014; Soares et al., 2015; Tamura et al., 2013; Teixeira et al., 2019; Vieira et al., 2003). Potential reasons for this controversy (e.g., the use of the Valsalva maneuver, time elapsed until measurement, position of measurement, and device employed for the measurement) are addressed in a systematic review with metanalysis derived from this thesis project. In addition to the exercise methodology itself, certain positions during the activity such as head-down positions could increase intraocular pressure (Y. W. Kim & Park, 2019; Wylęgała, 2016; Zhu et al., 2018). Considering the above concerns, it remains necessary to study sports disciplines that in their practice combine the aerobic and muscular systems and changes of position such as acrobatic gymnastics.

Ocular perfusion pressure

The role of vascular risk factors in the development of ocular conditions such as glaucoma is increasingly supported by the literature (Bowe et al., 2015; Tham et al., 2018; Topouzis & Panayiota, 2009; Trivli et al., 2019). In this sense, a low blood flow together with insufficient autoregulation may lead to unstable ocular perfusion and thereby to ischemia and reperfusion damage to the optic nerve fibers (Costa et al., 2014; Stodtmeister et al., 2013). This contributes to the structural and functional characteristics found in glaucoma patients, such as visual field loss (Parekh et al., 2018).

Blood flow in any tissue is determined by the ratio of the arteriovenous pressure gradient to the vascular resistance (Anderson, 1999; Sen et al., 2018; Van Keer et al., 2016). The arteriovenous pressure gradient, which is also called perfusion pressure, is the difference between arterial blood pressure and venous pressure (Anderson, 1999; Sen et al., 2018; Van Keer et al., 2016). The arterial blood pressure used for the calculations can be systolic, diastolic, or mean, and thereby values of systolic, diastolic, or mean perfusion pressure can be obtained (Costa et al., 2014).

As presented in Figure 5, in the eye, the optic nerve head is supplied by the central retinal artery, which is a branch of the ophthalmic artery that originates from the internal carotid artery (McAllister, 2013). Therefore, the blood pressure at the central retinal artery should be used to calculate the ocular perfusion pressure (Van Keer et al., 2016).

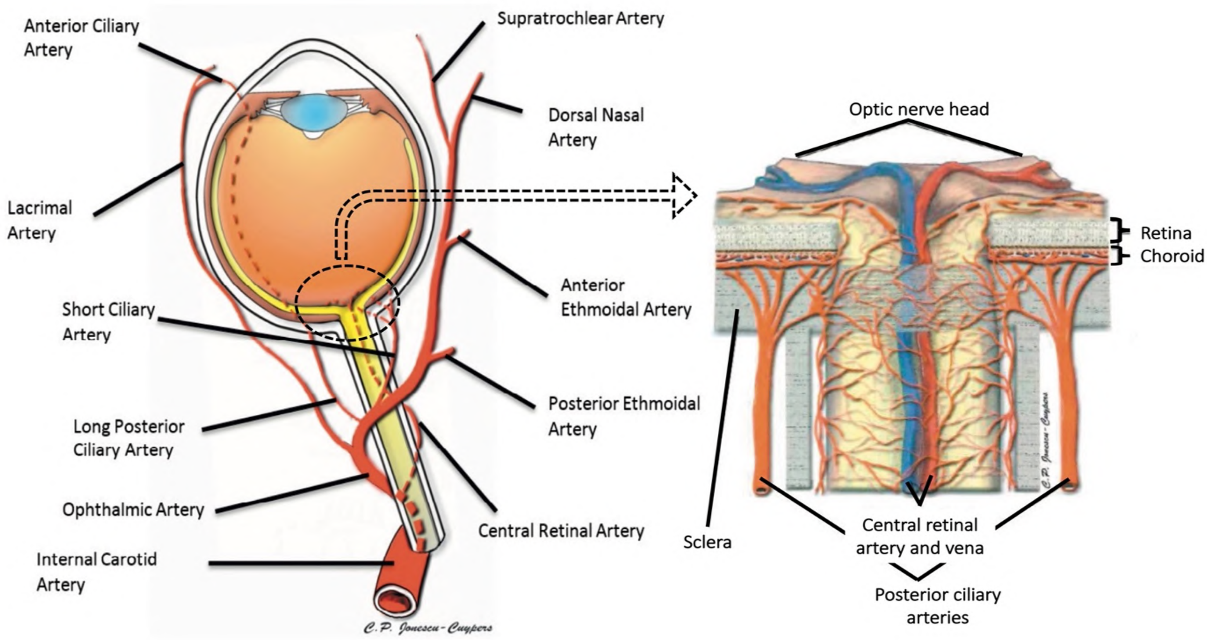

Figure 5. Vascular anatomy of the eye. Adapted from: Harris, A. (2002). *Atlas of ocular blood flow*. Butterworth-Heinemann; Parekh, P., Harris, A., Gross, J., Verticchio, A. C., & Siesky, B. (2018). Blood flow parameters of the optic nerve. In J. R. Samples & P. A. Knepper (Eds.), *Glaucoma research and clinical advances 2018 to 2020* (pp. 133–149). Kugler Publications.

Considering the inconveniences of directly measuring central retinal arterial pressure, brachial arterial pressure is used with a correction factor of two thirds to compensate for differences in flow resistance and hydrostatic pressures between the arm and eye (Longo et al., 2004; Riva et al., 2011; Van Keer et al., 2016). Additionally, intraocular pressure is used as a substitute for retinal venous pressure in the calculation of the ocular blood flow due to the so-called Starling resistor effect (Chan et al., 2016; Leske, 2009; Ngo et al., 2013; Patterson & Starling, 1914; Sen et al., 2018; Stodtmeister et al., 2013; Topouzis & Panayiota, 2009; Trivli et al., 2019; Van Keer et al., 2016). Therefore, ocular blood flow is estimated by ocular perfusion pressure, which is the formula for mean ocular perfusion pressure: 2/3 x mean brachial arterial blood pressure – intraocular pressure (see Section 1.2.2 for further information regarding how to calculate mean brachial arterial blood pressure). Although this is the most recognized formula in the literature, there is controversy regarding the correction factor and formulas to be employed (Barbosa-Breda et al., 2018; Costa et al., 2014; Van Keer et al., 2016). Our research group is conducting a study derived from this thesis to compare the values obtained with the different formulas after exercise.

Only a few studies have addressed the ocular perfusion pressure variations after dynamic resistance training exercises. The main findings have been mean ocular perfusion pressure decreases or nonsignificant changes together with intraocular pressure increments

(Vaghefi et al., 2021; Vera, Jiménez, Redondo, Torrejón, et al., 2018; Vera, Jiménez, Redondo, Torrejón, De Moraes, et al., 2019).

Central corneal thickness

Central corneal thickness is another parameter associated with ocular health (Hoffmann et al., 2013; Wang et al., 2014; T. T. Wong et al., 2009) and represents the distance from the anterior to the posterior cornea (Read & Collins, 2011) as Figure 3 shows. The normal central corneal thickness values have been established around 550 microns (Gupta et al., 2008; Hoffmann et al., 2013).

To the best of our knowledge, no previous studies have addressed the potential central corneal thickness acute adaptations that can occur due to resistance training. Previous research encountered nonsignificant variations after moderate-intensity bicycle ergometer exercise (Read & Collins, 2011) and a significant increment of the central corneal thickness in high-altitude climbing, although the variations could be attributed to low oxygen concentrations at high altitudes rather than to the exercise effect (Wylęgała, 2016).

The potential effects of using elastic bands to load the bar for squats on ocular parameters

As far as we know, no previous research has investigated the different acute adaptations that may occur in ocular parameters (i.e., intraocular pressure, ocular perfusion pressure, and central corneal thickness) when using elastic bands instead of weight plates to load the bar for squats. Concerning the potential use of elastic bands to preserve ocular health during squats, it is important to understand that in the deepest phases of the squat, a large increase in difficulty occurs (Kompf & Arandjelović, 2016, 2017). This increases the effort of the core and respiratory muscles and the intrabdominal and intrathoracic pressure (Blazek et al., 2019), which decreases the venous return through the vena cava as happens during the Valsalva maneuver (Y. W. Kim & Park, 2019). Additionally, the choroidal volume and episcleral venous pressure increase; thereby, an elevation in intraocular pressure could be expected (Y. W. Kim & Park, 2019; McMonnies, 2016). Given that the elastic bands reduce the load throughout this biomechanically disadvantageous region of the movement due to their elongation coefficient (V. Andersen et al., 2016; Frost et al., 2010; Saeterbakken et al., 2016), the question arises as to whether the use of elastic bands in squats could generate different responses in ocular parameters compared to conventional resistance (e.g., weight plates).

1.2.2 Cardiovascular health

Concerning cardiovascular health, hypertension is the leading modifiable risk factor for cardiovascular disease and premature death, with a prevalence of approximately 33% worldwide (see Figure 6; NCD Risk Factor Collaboration, 2021).

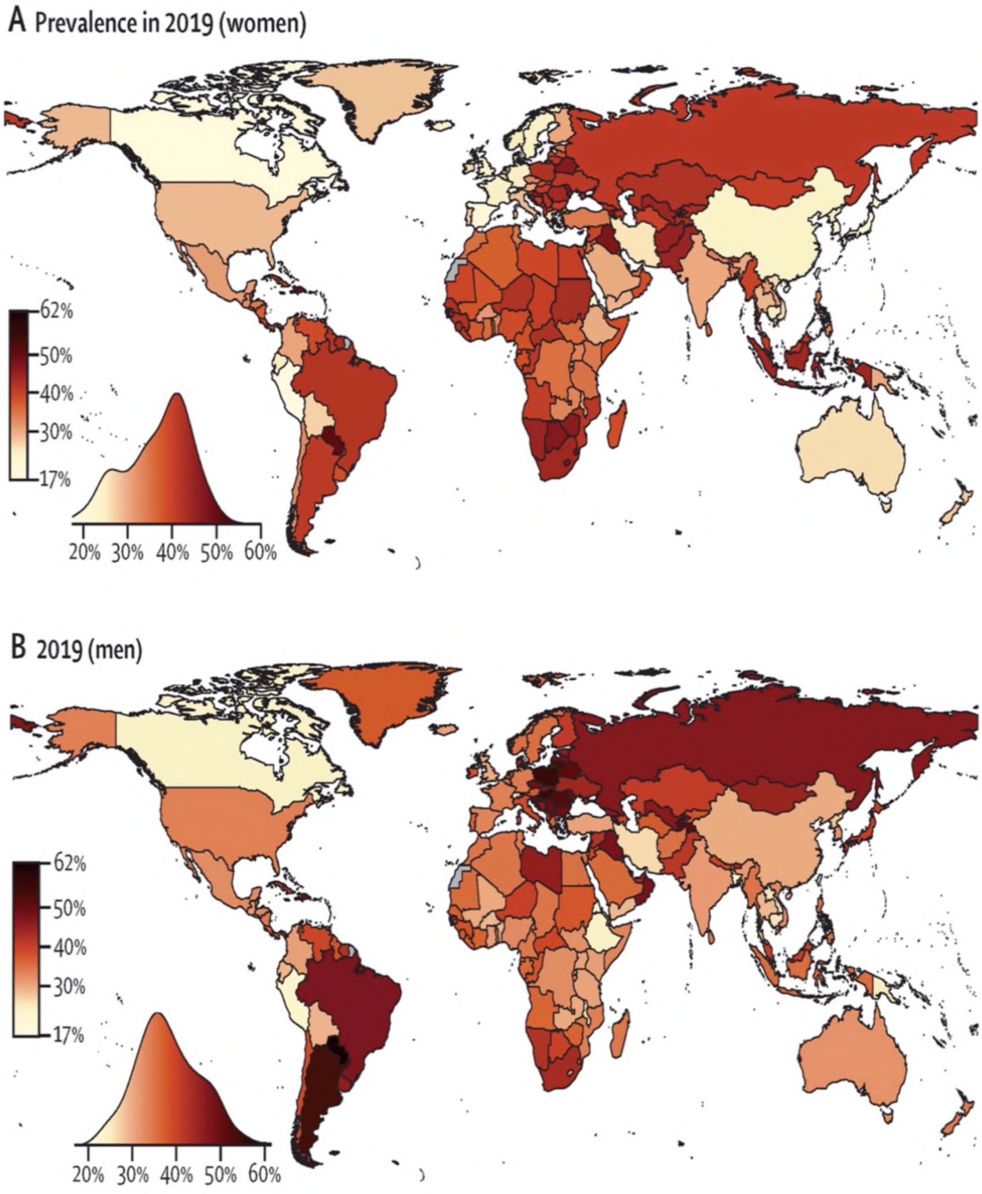

Figure 6. Hypertension prevalence by world region in 2019 (systolic blood pressure ≥ 140 mmHg; diastolic blood pressure ≥ 90 mmHg). Adapted from: NCD Risk Factor Collaboration. (2021). Worldwide trends in hypertension prevalence and progress in treatment and control from 1990 to 2019: A pooled analysis of 1201 population-representative studies with 104 million participants. The Lancet, 398(10304), 957–980.

Hypertension is a multifactorial and highly complex condition consisting of a persistent elevation of systemic blood pressure (i.e., systolic ≥ 140 mmHg and diastolic ≥ 90 mmHg; Hall et al., 2012; Memarzadeh et al., 2010; Ngo et al., 2013; Tham et al., 2018). This condition is associated with coronary heart disease, cerebrovascular disease, and renal disease (Foëx & Sear, 2004; Mills et al., 2020). Therefore, controlling for blood pressure values and their fluctuations is crucial to maintain cardiovascular health (Cornelissen et al., 2011).

Apart from being key factors in the control of cardiovascular (Caprioli & Coleman, 2010; Cornelissen et al., 2011; Nunes et al., 2021) and ocular health (Caprioli & Coleman, 2010; Cherecheanu et al., 2013; Karabatakis et al., 2004; McMonnies, 2016; Memarzadeh et al., 2010; Ngo et al., 2013; Tham et al., 2018; Trivli et al., 2019), blood pressure and heart rate are useful parameters to monitor internal load and performance (Halson, 2014; Iglesias-Soler et al., 2015) and are also acutely influenced by resistance training (Carpio-Rivera et al., 2016).

Blood pressure is dependent on the balance between the cardiac output and peripheral vascular resistance and is commonly measured by the systolic or diastolic brachial arterial blood pressure in mmHg (Beevers, 2001; Ogedegbe & Pickering, 2010). However, these measures are two specific inflection points of the blood pressure wave and are usually considered in isolation (Blacher et al., 2000; Franklin et al., 1999; Glasser et al., 2014). However, bearing in mind that blood pressure propagates through the arterial tree as a repetitive continuous wave, it is more accurately described as a pulsatile component (pulse pressure) and a steady component (mean pressure; Blacher et al., 2000; Dart, 2017; Dart & Kingwell, 2001). Therefore, arterial blood pressure in the largest vessels is better represented by the four components of blood pressure (systolic and diastolic blood pressure, pulse pressure, and mean arterial blood pressure) as represented in Figure 7.

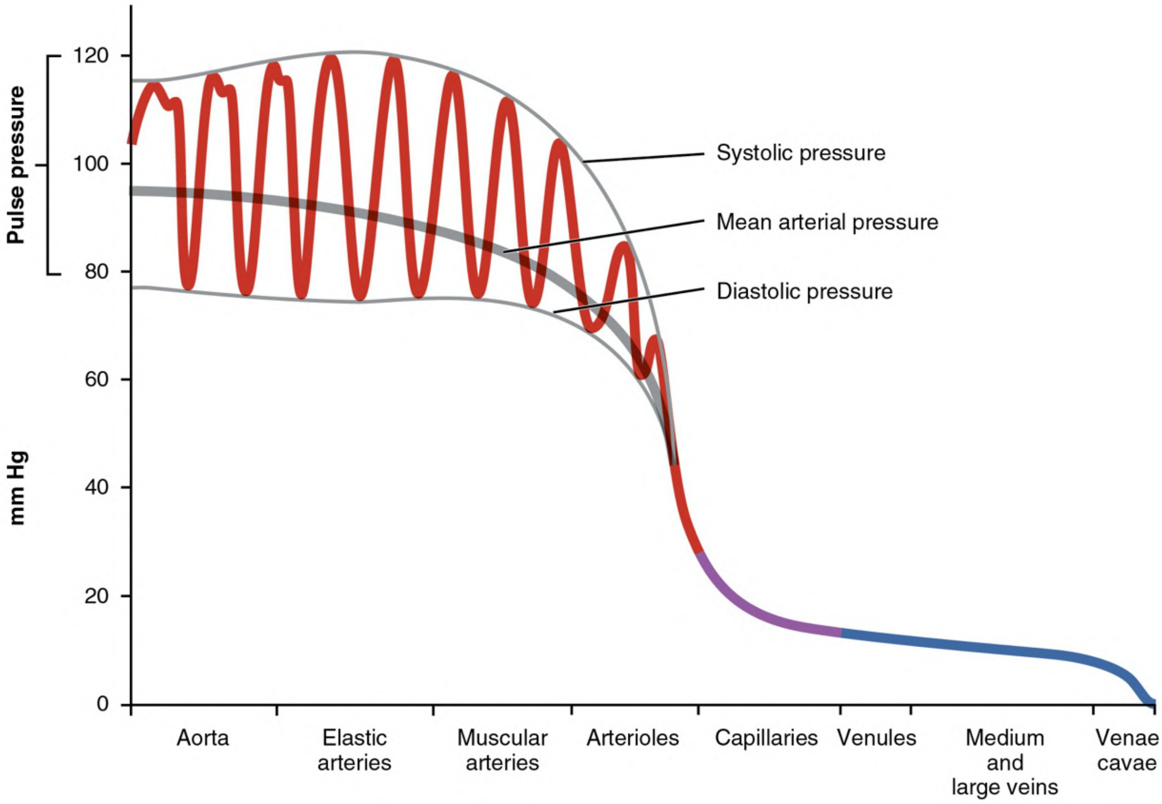

Figure 7. Components of blood pressure (systolic and diastolic blood pressure, pulse pressure, and mean arterial blood pressure) throughout the blood vessels. Retrieved from: Betts, J. G., Desaix, P., Johnson, E., Johnson, J. E., Korol, O., Kruse, D., Poe, B., Wise, J. A., Womble, M., & Young, K. A. (2017). *Anatomy & physiology*. OpenStax.

Systolic and diastolic blood pressure

Systolic blood pressure is defined as the maximum pressure experienced in the aorta when the heart contracts and ejects blood into the aorta from the left ventricle (approximately 120 mmHg; Homan et al., 2021). Diastolic blood pressure is the minimum pressure experienced in the aorta when the heart relaxes before ejecting blood into the aorta from the left ventricle (approximately 80 mmHg; Homan et al., 2021).

Persistent resting values of systolic blood pressure between 120 and 139 mmHg or diastolic blood pressure between 80 and 89 mmHg are considered prehypertension, a precursor of clinical hypertension (Sreenivas et al., 2018). Values of systolic blood pressure > 220 mmHg and/or diastolic blood pressure > 120 mmHg have been established by the British National Formulary as the limit to start immediate therapy (Foëx & Sear, 2004). All values below that should be confirmed over one to four weeks before starting treatment (Foëx & Sear, 2004).

Pulse pressure

Pulse pressure is receiving increased attention as a predictor of cardiovascular risk due to being an indicator of cardiovascular disease in the general term and, more specifically, of the stiffness of large arteries, especially the aorta (Buda et al., 2018; Glasser et al., 2014; Homan et al., 2021). In this regard, pulse pressure depends on stroke volume, arterial stiffness, and the timing of wave reflections (Blacher et al., 2000; Buda et al., 2018; Dart, 2017; Dart & Kingwell, 2001).

As Figure 7 illustrates (Betts et al., 2017), the pulse pressure is obtained with the formula systolic blood pressure – diastolic blood pressure (Buda et al., 2018; Glasser et al., 2014; Homan et al., 2021).

Considering the normal systolic blood pressure at 120 mmHg, the normal diastolic blood pressure at 80 mmHg, and the blood pressure variation within a cardiac cycle, the normal pulse pressure is approximately 40 to 60 mmHg (Homan et al., 2021; Weinreb et al., 2015). However, resistance-trained individuals can present higher pulse pressure values (Bertovic et al., 1999). Some studies associate a pulse pressure above 60 to 65 mmHg with an increased risk of cardiovascular complications (Dart & Kingwell, 2001; Glasser et al., 2014).

Mean arterial blood pressure

Mean arterial blood pressure is also considered a key cardiovascular variable in exercise physiology and health (Rogers & Oosthuyse, 2000; Sainas et al., 2016). It represents the average arterial pressure during a full heart cycle (systole and diastole; DeMers & Wachs, 2020) and determines the perfusion pressure through tissue beds (Chemla et al., 2002; Papaioannou, Protogerou, Vavuranakis, et al., 2016; Sainas et al., 2016) and therefore the blood supply to organs (Brzezinski, 1990). Mean arterial blood pressure is mainly determined by cardiac output and peripheral vascular resistance (Blacher et al., 2000; Buda et al., 2018; Dart, 2017; Dart & Kingwell, 2001).

Mean arterial blood pressure is calculated by adding the systolic and diastolic blood pressure and computing their time-averaged fraction of the cardiac cycle as per the blood pressure waveform configuration (Papaioannou, Protogerou, Vavuranakis, et al., 2016; Papaioannou, Protogerou, Vrachatis, et al., 2016; Rogers & Oosthuyse, 2000; Vos et al., 2013). Written in a formula, mean arterial blood pressure = (diastolic period as a fraction of cardiac cycle x diastolic blood pressure) + (systolic period as a fraction of cardiac cycle x systolic blood pressure). This formula can be reduced (see Rogers & Oosthuyse [2000] for further information) to mean arterial blood pressure = diastolic blood pressure + systolic period as a fraction of cardiac cycle x (systolic blood pressure – diastolic blood pressure). The standard, most commonly used formula follows the assumption of the duration of the diastole being two thirds the cardiac cycle and the systole one third; therefore, mean arterial blood pressure = diastolic blood pressure + 1/3 x (systolic blood pressure – diastolic blood pressure). However, previous research has proposed different values for the constant and adjustment for heart rate increments (Papaioannou, Protogerou, Vrachatis, et al., 2016; Razminia et al., 2004; Sainas et al., 2016). To address this issue, our research group is conducting a study to identify the potential differences that the use of each different formula could entail to measure mean arterial blood pressure after exercise.

A minimum mean arterial blood pressure of 60 mmHg is required to maintain adequate perfusion to vital organs (DeMers & Wachs, 2020). However, organ damage can occur if the mean arterial blood pressure is excessively elevated since prolonged exposure to elevated pressures is associated with an increased incidence of cardiovascular disease (Brzezinski, 1990; Papaioannou, Protogerou, Vrachatis, et al., 2016).

The potential effects of using elastic bands to load the bar for squats on cardiovascular parameters

Resistance training provokes an acute immediate increase in heart rate (Castinheiras-Neto, 2010; De Souza et al., 2013; Dos Prazeres et al., 2017; Gjovaag et al., 2016; Howard et al., 2018; Nunes et al., 2021) and systolic, diastolic, and mean arterial blood pressure and pulse pressure (Castinheiras-Neto, 2010; Dos Prazeres et al., 2017; Gjovaag et al., 2016; Gotshall et al., 1999; Iglesias-Soler et al., 2015; Rogers & Oosthuyse, 2000) due to, among other factors, a rise in cardiac output (Goldring et al., 2014). However, resistance training has been shown to reduce resting blood pressure in the long term (Oliver-Martínez et al., 2020), probably due to a reduction in vascular stiffness and peripheral vascular resistance due to lowered sympathetic activity, higher production of nitric oxide and its associated vasodilator effect, and sustained postexercise vasodilation of the previously active skeletal muscle, among other factors (De Souza et al., 2013; Oliver-Martínez et al., 2020).

Considering the higher intra-abdominal and intrathoracic pressures within the deepest phases of the squat, which increases blood pressure (Blazek et al., 2019), elastic bands could be an appropriate alternative to weight plates when aiming to obtain conservative cardiovascular responses due to the weight reduction in the deepest phases.

1.3 Aims of the present research project

The main objective of this doctoral thesis research was to assess the potential use of elastic bands to load the bar for squats and its relationship with ocular and cardiovascular health parameters, subjective effort, and performance. Two preliminary studies were designed to identify potential predictors of the intraocular pressure variations after exercise and select the most appropriate squat variation for the present project, respectively.

The specific aims, which were each addressed in one study, were designed to

1) Investigate intraocular pressure and central corneal thickness variations after combined exercise to assess a set of demographics (age and sex) and ocular parameters (baseline intraocular pressure and baseline central corneal thickness) as potential predictors of the intraocular pressure variation due to the exercise.

2) Obtain scientific knowledge on the squat exercise and each of its variations from a biomechanical, kinetic, and myoelectric perspective. More precisely, we aimed at identifying the specific characteristics of each squat variation to select the most appropriate variation for the present project.

3) Evaluate the differences in the squat performance and cardiovascular and perceptual responses (as measurements of the internal load) when exclusively using elastic bands or weight plates to load the bar. More specifically, we analyzed the potential of adding the pertinent load immediately above the sticking point to optimize the weight used and maximize the performance.

4) Analyze the effects of squatting with elastic bands on the intraocular pressure, mean ocular perfusion pressure, central corneal thickness, pulse pressure, and mean blood pressure as ocular and cardiovascular health-related parameters and compare the results with the use of weight plates to load the bar.

1.3.1 Hypotheses

Bearing in mind the scientific evidence presented in the introduction, it was hypothesized that

1) Intraocular pressure would be reduced after exercise, and central corneal thickness would remain unchanged. We also expected to find that the independent variables (age, sex, baseline intraocular pressure, and central corneal thickness) would mediate the intraocular pressure variations.

2) Depending on their application, elastic bands would allow subjects to perform a higher volume of repetitions with more weight in the standing position while presenting nonsignificant variations in the internal load.

3) Intraocular pressure would be reduced after exercise, and central corneal thickness would remain unchanged. Elastic bands would allow for lower intraocular pressure and higher mean ocular perfusion pressure values than weight plates would.

Chapters 2, 3, 4, and 5 each present one of the four studies composing the compendium of the present doctoral thesis with a lineal research progression. More specifically, the first study (Gene-Morales et al., 2021) was designed to evaluate sociodemographic or physiological predictors of the intraocular pressure variations provoked by exercise, the second (Gene-Morales, Flandez, et al., 2020) to deeply understand the squat movement, the third (Gene-Morales, Gené-Sampedro, et al., 2020) to evaluate different applications of elastic bands as a material to load the bar to maximize performance in resistance training, and the fourth (Gene-Morales et al., 2022) to compare the intraocular pressure variations provoked by squatting with elastic bands or weight plates.

Chapter 2. The prediction potential of sociodemographic and ocular parameters for the intraocular pressure variations

Do age and sex play a role in intraocular pressure changes after acrobatic gymnastics?

2. The prediction potential of sociodemographic and ocular parameters for the intraocular pressure variations that occur with exercise

Before evaluating the intraocular pressure variations provoked by squatting, we conducted a preliminary study with acrobatic gymnastics athletes to address the mediator role of sociodemographic and ocular parameters on the intraocular pressure variations (Gene-Morales et al., 2021). This study was conducted after an acrobatic gymnastics session at the gym to obtain a better understanding of the effects of this activity that could not be established within a laboratory environment.

Acrobatic gymnastics is a combined activity that can be performed in pairs or groups and includes static elements such as balances and figure holds (hand balances, bridges, splits, human pyramids) and dynamic elements such as partner lifts, throws with complex somersaults and twists, and tumbling skills (Fédération Internationale de Gymnastique, 2016, 2020). This motor and social sport requires high levels of strength, flexibility, balance, agility, coordination, speed, and cardiovascular performance (Höög & Andersson, 2021). Nevertheless, knowledge about acrobatic gymnastics remains incomplete (Taboada-Iglesias et al., 2017), especially in terms of ocular adaptations.

Additionally, previous research found nonsignificant central corneal thickness variations after moderate-intensity bicycle ergometer exercise (Read & Collins, 2011). Bearing in mind these results, the question arose whether posture changes that occur within acrobatic gymnastics (e.g., hand balances, somersaults, twists, tumbling skills) practice could affect central corneal thickness. No previous studies exploring intraocular pressure or central corneal thickness variations after acrobatic gymnastics were found. As far as we know, this is also the first study to analyze the potential effects of age, sex, baseline intraocular pressure, and baseline central corneal thickness on the intraocular pressure fluctuations caused by acrobatic gymnastics exercise.

2.1 Methods

An observational, prospective, longitudinal study was conducted to compare the intraocular pressure and central corneal thickness of gymnasts before and after exercise. Additionally, the prediction potential of age, sex, baseline intraocular pressure, and baseline central corneal thickness for the variation of intraocular pressure was addressed. We conducted the study in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki; Hutchinson, 2002), and ethical approval was provided by the University of

Valencia's Research Ethics Committee on human research (H1499867368458). The study was also approved by the Club Dynamic Gym of Manises (Valencia, Spain). Participants were informed of the study characteristics and protocols, and signed informed consent was obtained from them at the beginning of the procedure. Participants were free to withdraw from the study at any time. Data were confidential and participation was anonymous, implying no potential risks for the integrity of the subjects apart from those derived from the physical activity.

2.1.1 Participants

The sample size was determined by a priori power analyses, assuming an α of 0.05, power levels ($1 – ß$) of between 0.80 and 0.95, a nonsphericity correction of $\varepsilon = 1$, and an effect size of $f(V) = 0.45$ for analysis of variance (ANOVA) tests and $f^2 = 0.24$ for the regression analyses. Thus, 49 participants were recruited for this study. The main inclusion criteria were (1) older than 18 and younger than 40 years old; (2) experience with acrobatic gymnastics of at least six months and performing at least two days per week; (3) no musculoskeletal issues; (4) baseline intraocular pressure between 10.00 and 21.00 mmHg; (5) normal anterior chamber depth; and (6) no history of ophthalmic laser procedures, ocular surgery, traumatism, or use of topic/systemic medications potentially affecting the intraocular pressure. Subjects with a family history of glaucoma and contact lens wearers were excluded from this study.

At the beginning of the study, 51 athletes were recruited, but only 49 met the criteria (18 male and 31 female). All these participants voluntarily agreed to participate in the study. Participants were classified into two groups according to their age: (1) adults (> 25 years old) and (2) young adults (≤ 25 years old; Bonnie et al., 2015). Additionally, three more groups were formed regarding the baseline intraocular pressure levels (low, medium, and high). For such purpose, baseline intraocular pressure was divided into terciles (with limits at 14 and 17 mmHg) as previously reported (Caprioli & Coleman, 2008; J. H. Kim & Caprioli, 2018). Further characteristics of the sample, including demographics and spherocylindrical refraction values, are reflected in Table 1. The spherocylindrical refraction values were converted to power vector notation (M, J0, and J45). Refractive error was determined in terms of (1) the spherical equivalent (M component) and (2) a pair of Jackson crossed cylinder lenses oriented at 0°/90° (J0 component) and 45°/135° (J45 component) for the determination of astigmatism. Refractive error was measured to characterize the sample considering its potential influences on intraocular pressure (T. Y. Wong et al., 2003).

Table 1. Characteristics of the general sample (n = 49).

Variable	Mean	Standard deviation	95% confidence interval	
			Lower	Upper
Age (years)	27.67	7.10	25.66	29.69
M (D)	−0.86	1.62	−1.32	−0.41
J0 (D)	−0.01	0.31	−0.09	0.08
J45 (D)	−0.03	0.15	−0.07	0.02

M: spherical equivalent. J0 and J45: Jackson crossed cylinder lenses, representing the three components of refractive error in power vector notation. D: diopters.

All participants were instructed to avoid alcohol and tobacco consumption and not to perform vigorous exercise 24 hours before any programmed session. They were asked to sleep for at least 8 hours, not to consume stimulants, not to drink more than one liter of liquids (McMonnies, 2016), and not to perform prolonged near-vision tasks within the three hours before the trials (Vera, Jiménez, et al., 2017).

2.1.2. Procedures

All procedures were conducted in the same gymnastics facilities by the same researchers (one optometrist in charge of the measurements and one sport scientist responsible for the gymnastics session). All data were collected in a thermoneutral environment (~22°C and ~60% humidity), under the same lighting, and during the same period (between 7:20 and 9:10 p.m.) to reduce the effects of circadian rhythm variations in the eyes (Lau & Pye, 2012). Measurement tools were installed in a room next to the training facilities to improve access and performance of techniques. Two sessions separated by one week were scheduled: one for assessment of sociodemographic data, participants' characteristics, and systematized ophthalmological examination at baseline and a second session to conduct all experimental procedures to evaluate the dependent variables before and after the training session.

In the first session, to ensure the suitability of participants, an ocular examination was performed, including measurements of best-corrected visual acuity, subjective refraction, intraocular pressure (Auto Kerato-Refracto-Tonometer TRK-2P, Topcon, Tokyo, Japan), stereopsis, motility, and biomicroscopic anterior eye segment examination (Slit Lamp SL-D4, Topcon Europe Medical BV, Capelle aan den Ijssel, Netherlands). Objective refraction was measured with the Auto Kerato-Refracto Tonometer (TRK-2P, Topcon, Tokyo, Japan) and was followed by a subjective refinement.

In the second session, preexercise eye parameters were measured 5 to 10 min before subjects began the exercise. All subjects underwent the same 90-min acrobatic gymnastics training session. Intraocular pressure and central corneal thickness were measured again 5 to 10 min after completion of the exercise.

Intraocular pressure and central corneal thickness

As reflected above, intraocular pressure and central corneal thickness were measured in mmHg and microns, respectively, with the Auto Kerato-Refracto-Tonometer TRK-2P (Topcon, Tokyo, Japan). This noncontact instrument is composed of Rotary Prism Technology, provides unmatched accuracy and reliability, and permits accurate and reliable measurements with a pupil as small as 2 millimeters in diameter. The device uses optical pachymetry to determine central corneal thickness, which involves using a tangential slit of light directed onto the cornea at a known angle. The illuminated slit is measured, and corneal thickness is calculated using trigonometry. All parameters, including horizontal and vertical alignment and vertex distance, were determined by the instrument. Additionally, TRK-2P allows adjusting the value of pneumotonometry with pachymetry so that it automatically adjusts the intraocular pressure value based on corneal thickness (Kocamis & Kilic, 2019). The measurements were taken using the full screening mode, which includes intraocular pressure, keratometry, autorefraction, and pachymetry values. Three readings for each patient were obtained, averaged, and recorded.

Measurements of both eyes were taken in this study. Right eye measurements were used since no significant difference ($p = 0.112$) was observed between the eyes.

<u>2.1.3 Statistical analysis</u>

First, a basic data curation was performed, and descriptive statistics of the sample features were calculated. The variation of intraocular pressure was calculated as postexercise intraocular pressure minus preexercise intraocular pressure and was converted to a percentage (Δ%). The normality of data distribution and homoscedasticity were assessed through the Shapiro–Wilk and Levene tests, respectively. The data showed a normal-Gaussian distribution with homogeneous variances.

At this point, a mixed factorial ANOVA with the exercise (preexercise and postexercise measurements) as the within-subject factor and sex (male, female), age (young adult, adult), and baseline intraocular pressure levels (low, medium, high) as the between-subject factors was used to evaluate the effects of the exercise and assess differences in the study-dependent variables. Effect size was evaluated with partial eta squared (ηp^2), where $0.01 < \eta p^2 < 0.06$ constitutes a small effect, $0.06 \leq \eta p^2 \leq 0.14$ constitutes a medium effect, and $\eta p^2 > 0.14$ constitutes a large effect. Pairwise post-hoc comparisons were evaluated using Bonferroni correction. The effect size for post-hoc comparisons was calculated as Cohen's *d* with Hedges' corrections to avoid biases due to sample size or standard deviation differences (Lakens, 2013). This corrected value is reported as unbiased Cohen's *d* (d_{unb}; Cumming, 2014), with $d_{unb} < 0.50$ constituting a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect (Cohen, 1988).

Afterward, multiple linear regression analyses (MLR–method: enter) were conducted for the variation of intraocular pressure (the difference between postexercise and preexercise intraocular pressure values). Two models' fit were tested as potential predictors of the intraocular pressure variation, one including sociodemographic (age and sex) and the other ocular variables (baseline levels of intraocular pressure and baseline central corneal thickness).

All the statistical analyses were conducted using the software IBM Statistical Package for the Social Sciences (SPSS) for Macintosh (Version 26.0, IBM Corp., Armonk, NY, USA), while statistical power analyses were completed with the software G*Power version 3.1.9.6 (Faul et al., 2007). The level of statistical significance was set at $p < 0.05$, and tendencies were identified from $0.05 \leq p \leq 0.13$.

2.2 Results

The ANOVA performed on intraocular pressure revealed significant effects of the exercise ($F[1, 43] = 33.77$, $p < 0.001$, $\eta p^2 = 0.46$), interaction exercise*sex ($F[1, 43] = 6.53$, $p = 0.015$, $\eta p^2 = 0.14$), and exercise*age ($F[1, 43] = 7.76$, $p = 0.008$, $\eta p^2 = 0.17$). The interaction exercise*baseline intraocular pressure was nonsignificant, although with a medium effect size ($F[2, 43] = 1.70$, $p = 0.196$, $\eta p^2 = 0.08$). All the rest of the interactions analyzed were not significant ($p > 0.05$). Regarding the central corneal thickness, the analysis of variance revealed a nonsignificant effect of exercise ($F[1, 43] = 3.97$, $p = 0.05$, $\eta p^2 = 0.09$) and of the interactions analyzed (exercise*sex: $F[1, 43] = 3.62$, $p = 0.064$, $\eta p^2 = 0.09$; exercise*age: $F[1, 43] = 0.70$, $p = 0.407$, $\eta p^2 = 0.02$; exercise*baseline intraocular pressure levels ($F[2, 43] = 0.24$, $p = 0.788$,

$\eta p^2 = 0.01$). Table 2 presents the general results of the sample. It is worth highlighting that while intraocular pressure was significantly modified ($p < 0.001$) with a moderate to large effect size ($d_{unb} = 0.73$) as a consequence of the exercise, central corneal thickness showed nonsignificant differences from preexercise to postexercise experimental points ($p = 0.229$).

Table 2. Data comparison between the preexercise and postexercise intraocular pressure values in the study participants ($n = 49$).

	Preexercise	Postexercise	Δ%	*p*-value	Cohen's d_{unb}
IOP (mmHg)	15.28 ± 0.95 [14.78–15.83]	14.30 ± 1.61 [13.93–14.97]	−6.27	< 0.001	0.73
CCT (microns)	557.34 ± 35.51 [544.78–566.05]	557.91 ± 35.23 [545.98–566.94]	0.19	0.229	0.03

Post-hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). Cohen's d_{unb} represents the effect size of the preexercise and postexercise differences, with $d_{unb} < 0.50$ being a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect.

2.2.1 Between-group comparisons

Bonferroni's post-hoc comparisons for the intraocular pressure and central corneal thickness results are presented in Table 3 (sex), Table 4 (age), and Table 5 (baseline intraocular pressure levels grouping). First, regarding between-sexes comparisons, significant differences were found in preexercise ($p = 0.01$, $d_{unb} = 0.59$) and postexercise intraocular pressure ($p = 0.04$, $d_{unb} = 0.45$) but not in the central corneal thickness (preexercise, $p = 0.097$; postexercise, $p = 0.071$). Highly significant differences were detected between sexes in the value of the variation of intraocular pressure (Δ%) with a significantly higher reduction found in males (mean difference 1.60 mmHg, 95% confidence interval [1.11–2.13], $p < 0.001$, $d_{unb} = 1.50$). Concerning the preexercise and postexercise comparison (within-group comparison), on the one hand, male athletes obtained a significant decrease in intraocular pressure with a large effect size ($d_{unb} = 1.02$). On the other hand, the variation of this variable was nonsignificant in females ($p = 0.312$). It is also remarkable that central corneal thickness was significantly modified ($p = 0.007$) from preexercise to postexercise in females, with the effect size being negligible ($d_{unb} = 0.03$).

Table 3. Data comparison between the preexercise and postexercise intraocular pressure values according to the sex of the participants (males, $n = 18$; females, $n = 31$).

	Group	**Preexercise**	**Postexercise**	**Δ%**	***p*-value**	**Cohen's d_{unb}**
IOP (mmHg)	Male	15.60 ± 1.31 * [15.28–16.04]	13.82 ± 2.29 * [13.06–14.38]	−11.41 **	< 0.001	1.02
	Female	14.91 ± 1.04 [15.11–15.71]	14.73 ± 1.81 [14.66–15.70]	−1.20	0.312	0.15
CCT (microns)	Male	546.94 ± 57.95 [526.11–559.51]	546.66 ± 57.13 [526.93–559.85]	0.09	0.395	0.01
	Female	568.02 ± 45.73 [554.84 –581.20]	569.53 ± 45.09 [556.54–582.52]	0.27	0.007	0.03

Post-hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). * and ** indicate statistically significant and highly statistically significant differences between sexes, respectively. Cohen's d_{unb} represents the effect size of the preexercise and postexercise differences, with $d_{unb} < 0.50$ being a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect.

The post-hoc analyses performed for age (Table 4) showed significant between-group differences in the postexercise intraocular pressure values (mean difference 1.17 mmHg, 95% confidence interval [1.12–1.22], $p = 0.016$, $d_{unb} = 0.50$) but not in the preexercise values (mean difference 0.02 mmHg, 95% confidence interval [0.01–0.05], $p > 0.05$). Additionally, both age groups showed a statistical tendency of significantly different intraocular pressure variation (Δ%) with a moderate effect size (mean difference 0.75 mmHg, 95% confidence interval [0.09–0.98], $p = 0.07$, $d_{unb} = 0.50$). Only the subjects over 25 years old presented significant ($p < 0.001$) intraocular pressure fluctuations from preexercise to postexercise with a moderate to large effect size ($d_{unb} = 0.78$). The young adults did not show significant fluctuations with the exercise ($p = 0.154$). No significant changes were observed for either of the groups in terms of the central corneal thickness (young adults: $p = 0.605$; adults: $p = 0.243$).

Table 4. Data comparison between the preexercise and postexercise intraocular pressure values according to the age of the participants (young adults [≤ 25 years old], $n = 21$; adults [> 25 years old], $n = 28$).

	Group	Preexercise	Postexercise	Δ%	*p*-value	Cohen's d_{unb}
IOP (mmHg)	Young adults	15.27 ± 1.30 [14.89–15.64]	14.88 ± 2.21 * [14.25 –15.52]	−2.55	0.154	0.21
	Adults	15.25 ± 1.39 [14.84–15.65]	13.71 ± 2.37 [13.03–14.40]	−10.10	< 0.001	0.78
CCT (microns)	Young adults	564.62 ± 58.28 [547.78–581.46]	564.95 ± 57.74 [548.27–581.64]	0.06	0.605	0.00
	Adults	550.05 ± 62.57 [531.97–569.13]	550.87 ± 62.00 [532.95–568.78]	0.15	0.243	0.01

Post-hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). "*" indicates statistically significant differences between age groups. Cohen's d_{unb} represents the effect size of the preexercise and postexercise differences, with $d_{unb} < 0.50$ being a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect.

Regarding the baseline intraocular pressure, significant differences were found in the postexercise intraocular pressure values as shown in Table 5. In fact, intraocular pressure variation (Δ%) was significantly lower in the participants with lower baseline intraocular pressure (≤ 14.00 mmHg) than in those with higher intraocular pressure at baseline (≥ 17.00 mmHg; mean difference 1.60 mmHg, 95% confidence interval [0.37–2.83], $p = 0.008$, $d_{unb} = 0.96$). The intraocular pressure variation (Δ%) in subjects with medium baseline intraocular pressure and those with higher intraocular pressure did not reflect statistical differences (mean difference 0.37 mmHg, 95% confidence interval [0.28–1.87], $p = 0.420$, $d_{unb} = 0.18$). Furthermore, while subjects with moderate (between 14.01 and 16.99 mmHg) and higher baseline intraocular pressure displayed significant ($p \leq 0.001$) intraocular pressure decreases with moderate effect sizes (d_{unb} from 0.57 to 0.74), subjects with lower baseline intraocular pressure did not show statistically significant differences ($p = 0.114$) with a small effect size ($d_{unb} = 0.25$).

Table 5. Data comparison between the preexercise and postexercise intraocular pressure values according to the baseline intraocular pressure of the participants (lowest [≤ 14.00 mmHg], n = 18; medium [14.01–16.99 mmHg], n = 17; highest [≥ 17.00 mmHg], n = 14).

	Group	Preexercise	Postexercise	Δ%	*p*-Value	Cohen's d_{unb}
IOP (mmHg)	Low	13.42 ± 1.43 ** [13.00–13.83]	12.91 ± 2.50 ** [12.19–13.63]	−3.80 [3]	0.114	0.25
	Medium	15.75 ± 1.44 ** [15.33–16.17]	14.56 ± 2.53 * [13.83–15.29]	−7.56	0.001	0.57
	High	17.44 ± 1.46 [17.02–17.86]	15.88 ± 2.56 [15.14–16.61]	−8.95	< 0.001	0.74
CCT (microns)	Low	551.58 ± 63.13 [533.39–569.77]	552.70 ± 62.24 [534.77–570.63]	0.20	0.136	0.02
	Medium	552.03 ± 63.86 [533.63–570.42]	553.24 ± 62.97 [535.10–571.38]	0.22	0.111	0.02
	High	562.65 ± 64.79 [543.98–581.31]	563.44 ± 63.88 [545.03–581.84]	0.14	0.303	0.01

Post-hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). * and ** indicate statistically significant and highly statistically significant differences from the rest of the groups, respectively. [3]: significant differences from Group 3 (high baseline IOP). Cohen's d_{unb} represents the effect size of the preexercise and postexercise differences, with $d_{unb} < 0.50$ being a small effect, $0.50 \le d_{unb} \le 0.79$ a moderate effect, and $d_{unb} \ge 0.80$ a large effect.

Differences in intraocular pressure variation (postexercise minus preexercise) of each of the three groups of participants that were subdivided by intraocular pressure values can be found in Figure 8. It is worth mentioning that some subjects of the lower-tercile group (baseline intraocular pressure under 14.00 mmHg) and a few of the upper-tercile group (baseline intraocular pressure over 17.00 mmHg) had their intraocular pressure increased due to the exercise effect, as the boxplots on the left and right show. Significant differences were encountered between the lower- and upper-tercile groups ($p = 0.008$, $d_{unb} = 0.96$).

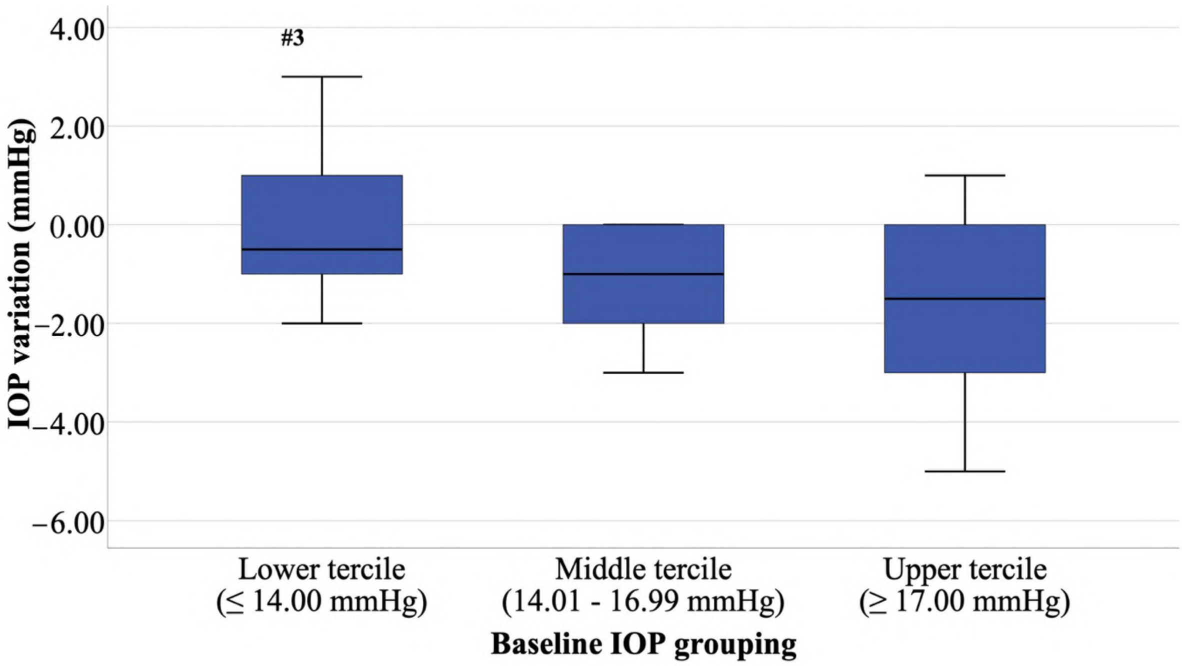

Figure 8. Intraocular pressure variation (postexercise intraocular pressure minus preexercise intraocular pressure) of each of the three groups formed considering the baseline intraocular pressure levels (lower: n = 18; middle: n = 17; upper: n = 14). Values of the vertical axis (intraocular pressure variation) are presented in mmHg. The symbol "#3" highlights significant differences from the upper-tercile group ($p = 0.008$, $d_{unb} = 0.96$).

2.2.2 Regression analyses

Multiple linear regression was calculated to potentially predict the intraocular pressure variation based on different features of the sample (age, gender, levels of baseline intraocular pressure, and levels of baseline central corneal thickness). A significant regression equation was found (F[3, 45] = 10.159, $p < 0.001$, with an adjusted R^2 of 0.433). Baseline central corneal thickness and age were discarded from the equation due to nonsignificant results. The predicted variation of intraocular pressure was equal to 1.430 (sex) – 0.270 (baseline intraocular pressure), where age is measured in years and the baseline intraocular pressure in mmHg. Regression analysis models are displayed in Table 6 where the significant model and its coefficients are described. Model 2 was retained since it was the one with the greatest prediction potential. This model predicted 43.3% of the variance in intraocular pressure. Sex and baseline intraocular pressure levels were significant ($p = 0.001$, and $p = 0.007$, respectively) predictors of the test outcomes. As shown in Table 6, while the baseline intraocular pressure levels were negatively correlated with the intraocular pressure variation, sex showed a positive correlation.

Table 6. Regression analyses.

Model	Predictor	Unstandardized coefficients		Standardized coefficients	*t*	Sig.	Adj. R^2	ΔR^2	Durbin-Watson
		B	S.E.	β					
1	(Constant)	−2.799	1.035		−2.704	0.010	0.358	0.284	1.975
	Age	−0.036	0.026	−0.164	−1.392	0.171			
	Sex	1.800	0.372	0.569	4.835	0.000			
2 *	(Constant)	−0.606	3.059		−0.198	0.844	0.433	0.096	
	Age	−0.035	0.024	−0.158	−1.429	0.160			
	Sex	1.430	0.383	0.452	3.730	0.001			
	Baseline IOP	−0.270	0.096	−0.322	−2.817	0.007			
	Baseline CCT	0.005	0.005	0.104	0.892	0.377			

IOP: intraocular pressure. CCT: central corneal thickness. *: retained model. B = unstandardized effect coefficient. S.E. = standard error. β = standardized effect coefficient (beta can be interpreted as controlling for the effects of other variables). *t* = value of the Student's t-test. Sig = *p*-value of the test. Adj. R^2 = adjusted R-square. ΔR^2 = changes in R-square.

2.3 Discussion

To the best of our knowledge, this is the first study to evaluate the effect of an acrobatic gymnastics session on intraocular pressure. Additionally, a set of variables were selected to potentially predict the variation of intraocular pressure. The most notable findings were that a session of acrobatic gymnastics significantly reduced the intraocular pressure values but did not significantly modify central corneal thickness (see Table 2), which is consistent with most previous studies on the effects of dynamic exercise on intraocular pressure (McMonnies, 2016; Wylęgała, 2016; Zhu et al., 2018) and confirms our first hypothesis. The small changes observed in central corneal thickness, such as those detected in females, could be due to physiological diurnal variations (Ariza-Gracia et al., 2015). Additionally, it is worth highlighting that sex and baseline intraocular pressure levels were significant predictors of the fluctuation of intraocular pressure due to the exercise (see Table 6), which only partially confirms the hypothesis of this first study. Accordingly, in a previous study, male gender and lower baseline intraocular pressure demonstrated a possible association with visual field loss progression (Nouri-Mahdavi et al., 2004).

Bearing the aforementioned results in mind, it is worth discussing the outputs of this research in the light of other empirical evidence that addressed the influence of the independent variables selected in this study (sex, age, baseline intraocular pressure) on intraocular pressure. However, caution should be applied when comparing different methodologies of exercise, and it should be borne in mind that the results presented in this study specifically concern acrobatic gymnastics.

First, sex could be a potential factor conditioning intraocular pressure due to sex hormones and genetic variants (Dane et al., 2003; Simcoe et al., 2020; Vajaranant et al., 2010). However, the findings encountered in the scientific literature are not consistent. Our results suggest that significant differences exist in both the baseline and postexercise intraocular pressure values (see Table 3). Furthermore, while males had their intraocular pressure significantly modified due to the exercise effect, the intraocular pressure of females did not change significantly. This is in contrast with authors who encountered nonsignificant between-sexes differences in intraocular pressure changes due to treadmill running and isometric efforts (Esfahani et al., 2017; Vera, Jiménez, Redondo, Torrejón, Koulieris, et al., 2019). On the other hand, the results presented concerning the sex of the participants are consistent with previous research that found differences between sexes (Era et al., 1993; Jeelani et al., 2014; Mori et al., 2000; Qureshi, 1997; Son et al., 2016) or identify sex as a confounding variable in the relationship between exercise and glaucoma (Lin et al., 2017). More specifically, a previous article (Vera, Jiménez, Redondo, Torrejón, Koulieris, et al., 2019) detected further intraocular pressure fluctuations in men compared to women after isometric squats. Further research needs to be done in this regard eliminating confounding variables to elucidate whether there is an actual difference between sexes in the intraocular pressure response to exercise and the origin of these differences.

Age has been widely studied as a conditioning factor of the intraocular pressure with significant positive correlations (Baek et al., 2015; Esfahani et al., 2017; Jeelani et al., 2014; T. T. Wong et al., 2009). Only one study was found that reports nonsignificant correlations between age and intraocular pressure (Rochtchina et al., 2002). The American Academy of Ophthalmology recognizes the age of 40 as the cutoff criterion to start comprehensive medical eye evaluation screening (Machiele et al., 2021). Therefore, only subjects under 40 years old were selected for the study. Although age was excluded from the prediction equation and was not correlated with intraocular pressure variations, significantly different behaviors were observed in the intraocular pressure of young adults under 25 years old and adults over 25. The present study not finding a significant correlation between age and intraocular pressure could be due to the age of the sample being limited to subjects under 40 years, with other studies reporting that the significant increase in baseline values occurs after the age of 40 (Qureshi, 1995). This is interesting and coincides with the information presented in Table 4. While the baseline intraocular pressure of both groups (under 40 years old) was not significantly different, the after-exercise intraocular pressure showed significant between-group differences with a moderate effect size (d_{unb} = 0.50). These results suggest that once finished with the effort, the young adults under 25 years old more quickly return to preexercise values than adults over 25 years old do. This could be due to the compensatory mechanisms in charge of maintaining tissue stability (J. H. Kim & Caprioli, 2018), which may function better in younger subjects, as demonstrated in rats (Jiang et al., 2018).

As for the third independent variable included in this study, it is worth highlighting that intraocular pressure followed different behaviors in subjects with medium and high baseline intraocular pressure compared to subjects with lower baseline intraocular pressure (see Table 5). This is consistent with previous research that encountered larger fluctuations in subjects with higher baseline intraocular pressure and less pronounced fluctuations in subjects with lower baseline intraocular pressure (Caprioli & Coleman, 2008; J. H. Kim & Caprioli, 2018; Tojo et al., 2016). More specifically, the expert literature reports larger postexercise decreases in subjects with higher pretest values (Ashkenazi et al., 1992; Era et al., 1993; Leighton & Phillips, 1970; Najmanova et al., 2016). In contrast, one study encountered a significant negative correlation between baseline intraocular pressure and its change (elevation) after an incremental running test (Najmanova et al., 2018) and other nonsignificant correlations (Price et al., 2003). The results presented are to be considered of relevance bearing in mind that subjects with lower intraocular pressure are more susceptible to optical nerve damage with fluctuations (Caprioli & Coleman, 2008; Nouri-Mahdavi et al., 2004). The baseline level of intraocular pressure influences the postexercise intraocular pressure and therefore, this should be a factor to consider in the management of subjects with glaucoma risk factors.

Finally, the analysis and comparison with animal studies could clarify the behavior of intraocular pressure with exercise. For instance, Castro et al. (2015) found positive results in the intraocular pressure of rats on a high-fructose diet with treadmill exercise at low intensity. These authors proposed as potential underlying mechanisms improved insulin sensitivity, reduced arterial pressure, and diminished peripheral sympathetic modulation (Castro et al., 2015). Additionally, one study reported that swimming can reverse the negative impact of aging on rats' optic nerve function (Chrysostomou et al., 2014). As reported by previous expert literature, exercise-related intraocular pressure diminishments could be related to lower norepinephrine concentrations, increased colloid osmotic pressure, coaction of nitric oxide and endothelin after exercise, and the β2-adrenergic receptor gene polymorphism (Gale et al., 2009; Martin et al., 1999; Risner et al., 2009). Future studies should evaluate the specific mechanisms that led to lower postexercise intraocular pressure with acrobatic gymnastics.

2.3.1 Limitations

Although all the procedures conducted in this study were carefully designed and supervised, several limitations should be listed. Validated noncontact air-puff tonometry was chosen because it is easy to use and does not require the use of anesthesia (Kato et al., 2018; Radhakrishnan et al., 2018). However, one should bear in mind that the values presented in this study are only preexercise and postexercise values. In this regard, continuous monitoring devices (Y. W. Kim et al., 2015) would provide the scientific literature with relevant information on what exactly happens during the practice. Additionally, future studies should address the time needed for intraocular pressure to return to preexercise values with similar exercise procedures. As per the results on the different intraocular pressure behaviors depending on the age of subjects, it could be interesting to include adults over 40 years of age in a similar study design. Finally, and as presented in the introduction, the importance of field-based studies like this is unnegotiable; however, it could be of great scientific interest to continuously monitor intraocular pressure while performing somersaults and/or tumbling skills in a controlled laboratory environment.

2.4 Conclusion

In summary, intraocular pressure significantly decreased and central corneal thickness remained unchanged from preexercise to postexercise. The intraocular pressure of males was significantly lowered from baseline to the end of the study. On the other hand, females did not reflect significant intraocular pressure changes. Similarly, the intraocular pressure of adults was further reduced compared to that of young adults. Finally, subjects with higher intraocular pressure at baseline (middle and upper terciles) had more pronounced decreases than the participants with lower intraocular pressure did. Sex and baseline intraocular pressure were discovered as significant predictors of intraocular pressure variation. The combination of findings presented herein could be of interest for the programming of physical exercise for coaches and ophthalmologists or optometrists in the prevention, management, and control of risk factors associated with intraocular pressure and glaucoma.

Chapter 3. Analysis of the main squat variations

A systematic review of the muscular activation of the lower limbs with five different variations of the squat exercise

3. Analysis of the main squat variations

First, it is worth highlighting that we conducted two similar studies analyzing the deadlift (Flandez, Gene-Morales, Juesas, et al., 2020) and squat (Gene-Morales, Flandez, et al., 2020) to choose between both exercises based on scientific data. The squat was chosen due to starting the movement with the eccentric phase and not with the concentric phase as in the deadlift. Additionally, the squat presents further biomechanical advantages to test the usefulness of elastic bands to load the bar at different points of the range of motion compared to the deadlift. Future studies should evaluate the potential of adding the pertinent load at different points of the range of motion using elastic bands in the deadlift exercise.

The squat is one of the most studied exercises due to different factors (V. Andersen et al., 2016; Clark et al., 2012; Kompf & Arandjelović, 2017; Schoenfeld, 2010b). Although the squat movement involves synergistic hip, knee, and ankle flexion and extension (Clark et al., 2012; Escamilla et al., 2001; Iversen et al., 2017; Schoenfeld, 2010b; Vigotsky et al., 2019), squats can be performed in different ways with significant biomechanical and neuromuscular differences between them (Clark et al., 2012; Gene-Morales, Flandez, et al., 2020; Kompf & Arandjelović, 2017; Schoenfeld, 2010b; Van den Tillaar et al., 2014). Therefore, this second article of the compendium presents a systematic review aimed at comparing the most common squat variations from a biomechanical, kinetic, and myoelectric perspective to select the most appropriate variation to be included in the present doctoral thesis.

3.1 Methods

3.1.1 Search strategies

This systematic review was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines (PRISMA; https://www.prisma-statement.org; Hutton et al., 2015; Urrútia & Bonfill, 2010). Four databases (Web of Science, PubMed, Scopus, and SportDiscus), ProQuest, and *Strength and Conditioning Journal* were consulted to collect information.

The following terms were used: [“squat” OR “squat exercise” OR “high bar squat” OR “low bar squat” OR “overhead squat” OR “front squat”] AND [“EMG” OR “electromyography” OR “electromyographic activity” OR “muscle activation” OR “muscle activity”]. A third line was added with the following terms to include technical variations: [“stance width” OR “hip rotation” OR “Smith machine” OR “deep” OR “depth” OR “parallel” OR “partial” OR “quarter”]. Furthermore, the operator “NOT” was used in combination with the terms “balance,” “instability,” “unstable,” “bands,” “chains,” “injury,” “injured,” “unload,” and “therapeutic” to refine the results and exclude articles that did not follow the inclusion criteria.

3.1.2 Eligibility criteria

Studies written in English that examined muscle activation in the lower limbs in squats were included in the analyses. No temporal restrictions were used in the search. Inclusion criteria were a) including healthy subjects with no recent history of injury, b) using stable surfaces to perform the squats, and c) using a barbell with weight. On the other hand, exclusion criteria were a) using variable resistance (i.e., elastic bands, chains) to load the exercise, b) analyzing muscle activity of the upper limb, and c) analyzing isometric squats.

3.1.3 Article selection and data processing

Screening of titles and abstracts was initially conducted to identify potentially relevant studies. A standardized form was used to assess the eligibility of each article considering the inclusion-exclusion criteria. The flow diagram summarizing the study selection process after reading the titles and abstracts of the initial search can be found in Figure 9.

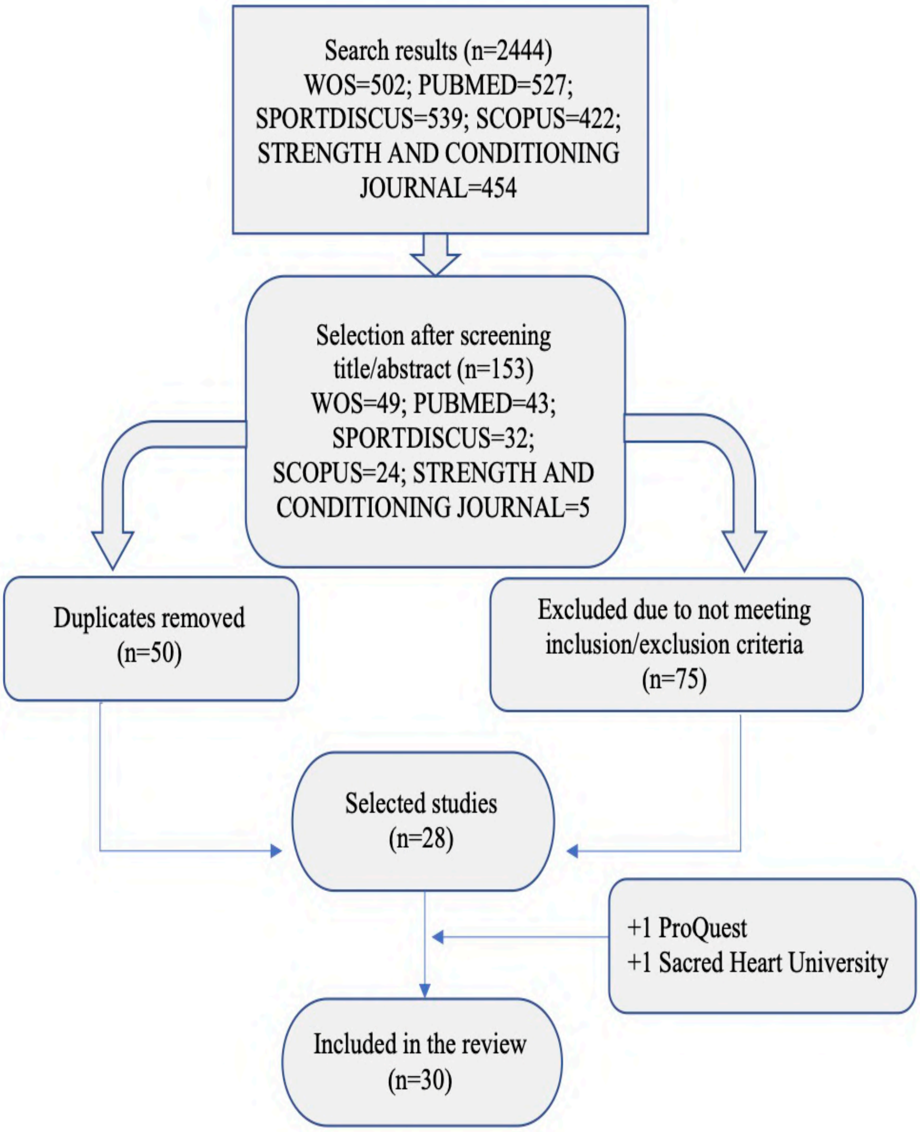

Figure 9. Flow diagram summarizing the study selection process from the first search to the final selection.

Squat variations

After carefully reading the selected articles, five squat variations were selected for the analysis by agreement between the authors. Some squat variations found in the literature and excluded from the analysis were the unilateral squat, Bulgarian squat, and wall squat. The four main squat variations included were the following (see Figures 10):

a) High-bar back squat (26 studies): the bar is placed across the shoulder on the trapezius slightly above the level of the acromion and the posterior aspect of the deltoids (Schoenfeld, 2010b; Vigotsky et al., 2019; Wretenberg et al., 1996). The high-bar back squat was in turn divided into full range of motion (i.e., the hips are lower than the knees), to parallel (i.e., lowering until the femur is parallel to the ground), and partial range of motion (i.e., half the range of motion of a parallel squat and a quarter of that of a full range of motion squat—approximately 45º of knee movement). Different technical variants of the squat exercise such as stance width and hip rotation planes were also included to enrich the analyses.

b) Front squat (five studies): the bar is held in front of the chest at the clavicle (Schoenfeld, 2010b).

c) Overhead squat (two studies): the bar is held with both hands, fully extended elbows, and externally rotated shoulders (Aspe & Swinton, 2014; Bautista, 2019).

d) Low-bar back squat (one study): the bar is placed slightly below the level of the acromion (Schoenfeld, 2010b; Wretenberg et al., 1996).

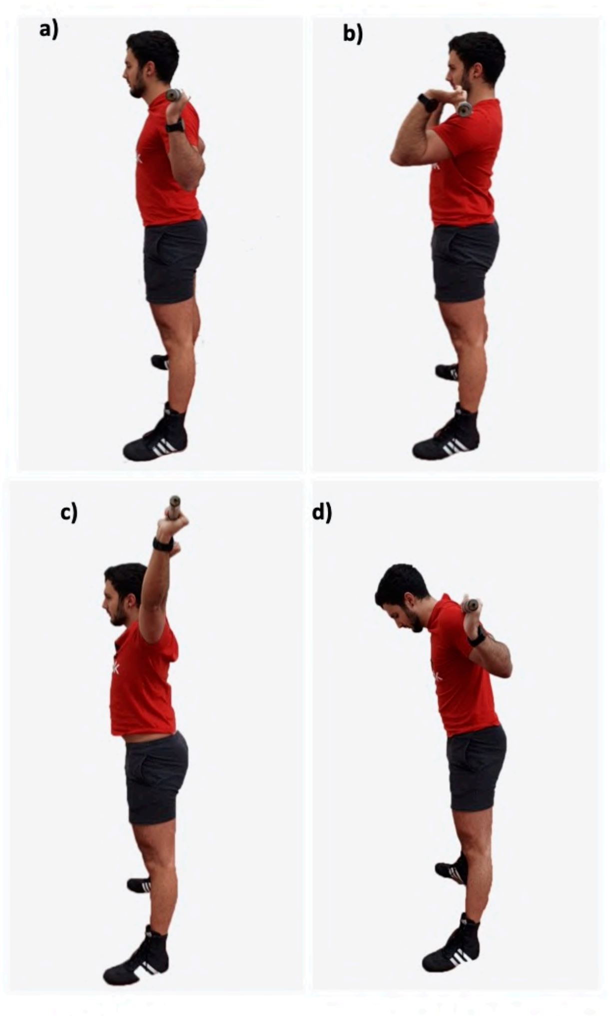

Figure 10. From left to right: a) high-bar back squat, b) front squat, c) overhead squat, d) low-bar back squat.

The guided squat using a Smith machine (two studies) was also included (see Figure 11). In this variation, the bar is guided and therefore can only be moved up and down. Different variations of the squat can be performed using a Smith machine, although for this study we only considered the high-bar back squat (Clark et al., 2012).

Figure 11. High-bar back squat performed using a Smith machine.

Electromyographical values and muscles analyzed

Electromyographical values are unequally reported among the expert literature not only concerning the units used (millivolts, microvolts, percentage of isometric maximum voluntary contraction, percentage of maximum voluntary contraction, percentage of root mean square values) but also for the measured phase (concentric and eccentric, mean of the set, mean of a repetition). For the present review, the values were standardized to facilitate comprehension and comparison between studies. For instance, values in millivolts were transformed into microvolts, and results of concentric and eccentric phases were averaged to obtain a single value.

After a thorough reading of the selected articles, the muscles to be included in the analysis were selected: a) gluteus maximus, b) gluteus medialis, c) hip adductors, d) vastus lateralis, e) vastus medialis, f) rectus femoris, g) biceps femoris, h) semitendinosus, i) tibialis anterior, j) gastrocnemius, and k) soleus. Muscles a, b, and c act mainly on the hips; muscles d, e, and f are part of the quadriceps and are mainly involved in knee extension; muscles g and h are part of the hamstrings, and their contraction mainly affects the knee flexion; the tibialis anterior (muscle i) is an ankle dorsiflexor; and finally, muscles j and k are part of the calves, and their action provokes an ankle extension. Previous expert literature (Netter, 1999) can be consulted for further information on the included muscles and anatomy.

3.1.4 Quality assessment

The quality of the included studies was analyzed using the PEDro scale (Maher et al., 2003). The scale was modified to fit the design of the included studies. Points 2 and 3 were unified into one point that assessed the randomization of the exercise conditions performed. Point 4 had to be excluded due to not including studies with control and experimental groups. Finally, points 5, 6, and 7 were also excluded due to the impossibility of blinding subjects or researchers. The resultant scale to evaluate the quality of the articles is composed of six items (Appendix 9.1.2).

3.2 Results

Thirty articles met the inclusion criteria and were reviewed (Appendix 9.1.2). The most studied variation of the squat exercise was the high-bar back squat (26 studies) followed by the front-squat (five studies), the overhead squat and the guided squat (both analyzed by two studies), and the low-bar back squat (one study). The main muscular group involved in all the variations was the quadriceps, with some differences between each squat variation and between different technical modifications (i.e., range of motion, stance width, hip rotation, feet placement).

Due to the considerable number of variations and exercise conditions, this section is divided into six subsections: one for each squat variation and one including the technical modifications of the exercise. Tables with the characteristics and main data of each article can be found in Appendix 9.1.2.

3.2.1 High-bar back squat

Most of the studies found the highest electrical activity in the vastus lateralis, vastus medialis, and rectus femoris in that order (Aspe & Swinton, 2014; Contreras et al., 2015, 2016; da Silva et al., 2017; Delgado et al., 2019; Ebben et al., 2009; Eliassen et al., 2018; Gorsuch et al., 2013; Hammond et al., 2016; Iversen et al., 2017; Korak et al., 2018; Robbins, 2011; Schwanbeck et al., 2009; Wu et al., 2019; Yavuz et al., 2015). Only one study found greater activation in the biceps femoris than on each of the three aforementioned muscles (V. Andersen et al., 2014). Regarding the activation in the gluteus and hamstrings, while some authors observed a greater activation in the gluteus maximus (Caterisano et al., 2002; Fauth et al., 2010; McCurdy et al., 2018), others reported a higher activity in the hamstrings (V. Andersen et al., 2014; Delgado et al., 2019; Gullett et al., 2009). Only three authors reported activation levels in the muscles of the calves when performing a high-bar back squat (Aspe & Swinton, 2014; da Silva et al., 2017; Schwanbeck et al., 2009).

3.2.2 Front squat

Muscle activity in this squat variation followed similar patterns to other squat variations (i.e., major activation in the vastus lateralis and medialis). Korak et al. (2018) reported similar activation levels in the rectus femoris and gluteus maximus. In contrast with the aforementioned authors, Gullet et al. (2009) found higher activation levels in the hamstrings than in the quadriceps.

3.2.3 Overhead squat

Two studies analyzed this variation of the squat exercise (Aspe & Swinton, 2014; Bautista, 2019). As happened with the rest of the variations, major activation levels were found in the vastus lateralis in both studies. In terms of secondary muscles, Aspe and Swinton (2014) reported higher activation levels in the gluteus maximus than in the biceps femoris. Bautista (2019) found lower activation levels in the biceps femoris but did not analyze the gluteus maximus.

3.2.4 Guided squat using a Smith machine

In one study, activation patterns were the same as those reported in the high-bar back squat (Schwanbeck et al., 2009). Blanpied et al. (1999) observed higher activation levels in the gluteus maximus than in the quadriceps or the hamstrings. The effects of a technical modification (i.e., feet placed in line with the body or ahead) when performing a guided squat could have influenced these results (Blanpied, 1999).

3.2.5 Low-bar back squat

Only the study of McCaw and Melrose (1999) analyzed the activation levels in the low-bar back squat and met the eligibility criteria. The main myoelectrical activity was observed in the vastus lateralis and medialis followed by the rectus femoris. Lower activity in the hip adductors and gluteus maximus in comparison to the quadriceps was observed. The myoelectrical activity of the hip adductors and gluteus maximus was similar. The lowest activation levels were detected in the biceps femoris.

3.2.6 Technical modifications

Range of motion

The effect of this technical modification was only assessed in the high-bar back squat. The comparison between three different depths (i.e., partial, parallel, and full squats) yielded similar activation patterns, with controversial results observed for the gluteus maximus activation (Caterisano et al., 2002; da Silva et al., 2017; Gorsuch et al., 2013; Hammond et al., 2016). While Caterisano et al. (2002) observed a slightly higher activation in the gluteus maximus in the full range of motion squats in comparison to the other two modalities, other authors found no differences or even higher gluteus maximus activity in the parallel squats (da Silva et al., 2017; Hammond et al., 2016).

Stance width

This technical modification was analyzed in the high-bar (Escamilla et al., 2001; Paoli et al., 2009) and low-bar (McCaw & Melrose, 1999) back squats. The main effect of having a wider stance was a higher activation in the gluteus maximus (McCaw & Melrose, 1999; Paoli et al., 2009). Variations of the stance width did not produce an effect on the activation of the quadriceps, hamstring, and gastrocnemius (Escamilla et al., 2001).

Hip rotation

Different hip rotations (i.e., orientation plane of the foot or knees) were only tested in the high-bar back squat. The main results of this technical modification were an increase in the activity of the hip adductors (Pereira et al., 2010). No significant effects of different hip rotations on the quadriceps were observed (Boyden et al., 2000).

Feet placement in line with the body or ahead

This technical modification was only tested in the guided squat since this machine allows the subject to place the feet in line with the body or ahead. When the feet were placed in line with the body, major activity in the quadriceps (i.e., the normal activity pattern of a high-bar back squat) was observed (Blanpied, 1999). In turn, when feet were placed in front of the body line, higher activity was detected in the gluteus maximus and hamstrings compared to the quadriceps (Blanpied, 1999).

3.3 Discussion

As a summary of this second article of the compendium that composes the present doctoral thesis, the major myoelectrical activity was found in the anterior thigh muscles, which are involved in the knee extension and are part of the quadriceps (i.e., vastus lateralis, vastus medialis, and rectus femoris), with the highest activation observed in the vastus lateralis. Only V. Andersen et al. (2014) and Gullet et al. (2009), reported higher activation levels in the hamstrings than in the quadriceps in the front squat and high-bar back squat, respectively. These uneven results may be due to the secondary function of the hamstrings as hip extensors (Netter, 1999). It should also be borne in mind that the hamstrings (biceps femoris, semitendinosus, and semimembranosus) are not actual antagonists in the squat exercise but cocontract with the quadriceps in their function of stabilizing the tibia and knee joint (Schoenfeld, 2010b). However, hamstring activation should only be moderate during the squat performance (Escamilla et al., 2001).

Regarding the comparison between the gluteus maximus and hamstring, there is some controversy about which have a higher activation (see Section 3.2.1). Attending to the squat biomechanics, the gluteus maximus act as a powerful hip extensor and as a knee and hip stabilizer (Netter, 1999). Gluteus maximus activation mainly depends on the muscle length, which is conditioned by various technique factors such as the depth and the stance width (McCaw & Melrose, 1999; Paoli et al., 2009; Schoenfeld, 2010b).

Concerning the calves, low activation levels have been observed in comparison to the thigh muscles (Aspe & Swinton, 2014; da Silva et al., 2017; Schwanbeck et al., 2009). Bearing in mind the main functions of the calves (Netter, 1999), these lower levels of activation may reside in the use of stable surfaces to perform the squat and the limited contribution of the ankle muscles in the squat movement.

As the results show, there are technical and electromyographical variations when the position of the bar changes (Pham et al., 2020). For instance, the load in the performance of a high-bar back squat, a front squat, or an overhead squat is shared between the knees and the hips (Comfort et al., 2018), with the main focus on the vastus lateralis and medialis as knee extensors (Aspe & Swinton, 2014; Contreras et al., 2015, 2016; Delgado et al., 2019; Ebben et al., 2009; Hammond et al., 2016). In turn, a higher hip involvement has been reported in the low-bar back squat (Glassbrook et al., 2017, 2019; Wretenberg et al., 1996). In this variation, the trunk inclination is greater, and thus gluteus and hip extensor activity is enhanced in comparison to other variations of the squat exercise. However, the low-bar back squat is still a knee extensor-dominant exercise (McCaw & Melrose, 1999). Further research on the electromyographic activity of this squat variation is needed to better understand the neuromuscular processes involved.

3.3.1 Comparing the activation levels of each variation

First, it is worth highlighting that higher levels of muscle activation are enhanced in the squat exercise with increasing loads (Aspe & Swinton, 2014; Boyden et al., 2000; McCaw & Melrose, 1999; Paoli et al., 2009). The lever arm between the external load (i.e., the barbell) and the center of mass of the body plays an important role in this regard (Gullett et al., 2009).

In the low-bar back squat, the lever arm is relatively shorter, and the position of the bar (below the acromion) is more biomechanically favorable than in the rest of the variations (see Figure 10; Glassbrook et al., 2017, 2019; Wretenberg et al., 1996). Due to the abovementioned facts, the low-bar back squat is the variation in which higher loads can be used and thus higher activation levels achieved. No significant differences were observed between the activation in high-bar back squats and front squats (Gullett et al., 2009; Korak et al., 2018), and therefore both would be classified at the same level after the low-bar back squat. Concerning the overhead squat, lower muscle activity on the lower limb has been observed in comparison to the aforementioned variations. This is due to the greater involvement of the upper body to hold the bar and stabilize the spine during the execution (Aspe & Swinton, 2014; Bautista, 2019). Moreover, there are factors such as strength and shoulder mobility that limit the load used in this exercise (Bautista, 2019). Since load increases entail increases in activation level (Aspe & Swinton, 2014; Boyden et al., 2000; McCaw & Melrose, 1999; Paoli et al., 2009), this squat variation should be positioned after the low-bar back squat, the high-bar back squat, and the front squat. Finally, Schwanbeck et al. (2009), Blanpied (1999), and Clark et al. (2012) highlight the squat performed using a Smith machine as the variation provoking the lowest activation levels on the stabilizers due to the guided nature of the exercise.

3.3.2 Technical factors that modify muscle activity patterns

Apart from the total load used, the depth has been shown to influence muscle activity patterns and level of activation. In this line, lower activation levels were observed in partial squats (i.e., approximately 45º of knee movement) compared with the parallel or full range of motion squats (Gorsuch et al., 2013; Hammond et al., 2016). Similarly, Paoli et al. (2010) observed that a reduction in the range of motion decreased muscle activation levels on the shoulder when performing a military press. This finding strengthens the idea that a greater range of motion entails greater muscle activation.

The stance width is another parameter that influences the muscle activity patterns in the squat. For instance, hamstrings, the gluteus maximus, and hip adductors have all shown significantly greater activity in the wider stance squat compared with the narrow stance (Escamilla et al., 2001; McCaw & Melrose, 1999; Paoli et al., 2009). One of the main functions of the gluteus maximus is hip abduction (Netter, 1999), and thus a wider stance facilitates this action of the gluteus maximus. No other muscle activity was altered with varying stance widths (Escamilla et al., 2001).

Finally, the rotation of the hips has been shown to increase the activation of hip adductors (Pereira et al., 2010) with no significant changes in the activation patterns of the rest of the analyzed muscles (Boyden et al., 2000).

3.3.3 Limitations

The included studies have some limitations that should be listed. First, it is worth mentioning that standardization values are uneven, and this may entail a problem when trying to compare and discuss results. Additionally, one study found significant differences between the upper and lower fibers of the gluteus maximus (Contreras et al., 2016). These differences between fiber bundles of the same muscle may condition electromyographical results.

In addition, even though all the procedures of the present review were carefully conducted, it is not free of limitations. For instance, standardized values may limit the analysis of each phase of the execution (i.e., eccentric, concentric). Future studies should review the literature comparing the activation in each phase of the squat exercise. Finally, the disparities between the included studies may cause incomplete comparisons and conclusions.

3.4 Conclusion

In summary, independent of the variation performed, the squat could be classified as a knee extensor-dominant exercise. The results show that the main determiner of muscle activation is the load employed. Therefore, the low-bar back squat (the variation in which greater loads can be employed due to the relatively short lever angle) is the variation in which greater muscle activity is obtained. However, greater hip flexion is required due to the position of the bar, and this provokes greater involvement of the hip muscles compared to other variations such as the high-bar back squat.

Bearing in mind all that has been mentioned in this chapter, for the studies of the present doctoral thesis, we selected the high-bar back squat performed using a Smith machine to a parallel depth with a shoulder-width stance, neutral feet orientation plane, and neutral hip rotation. This is the most commonly studied variation and the one with the most homogeneous results. Furthermore, the high-bar back squat presents biomechanical and technical advantages compared to other squat variations such as the overhead squat. The Smith machine was selected because it only permits vertical movement. This avoids instability and allows participants to focus exclusively on vertically pushing, which could be crucial when aiming to test a new methodology (i.e., adding the load immediately above the sticking point with elastic bands). Finally, parallel depth and neutral foot, knee, and hip orientation were selected because they produce similar activation patterns and reduce the technical requirements of the exercise.

Chapter 4. The potential use of elastic bands to maximize squat performance

Adding the load just above the sticking point using elastic bands optimizes squat performance, perceived effort rate, and cardiovascular responses

4. The potential use of elastic bands to maximize squat performance

As mentioned in Chapter 1, previous research has struggled to obtain enough load for squat exercises with elastic bands (Saeterbakken et al., 2016); therefore, the comparability of using elastic bands and weight plates for resistance training may be limited. In this regard, and bearing in mind the positive results obtained in several studies derived from this doctoral thesis that encountered performance improvements in different age groups with interventions based on performing resistance training with elastic bands (Flandez, Gene-Morales, Modena, et al., 2020; Hammami et al., 2021), it was hypothesized that attaching elastic bands to the bar immediately above the participants' sticking point in squats could significantly increase the and optimize the weight used throughout the range of motion. This could make the comparisons between weight plates and elastic bands more realistic.

Therefore, we conducted a quasiexperimental study to compare the squat performance when exclusively using elastic bands or weight plates to load the bar. A guided high-bar back squat was chosen according to the results of the second study of the present doctoral thesis (see Chapter 3; Gene-Morales, Flandez, et al., 2020). We also analyzed the potential of adding the pertinent load immediately above the sticking point to optimize the weight used and maximize the performance. To the best of our knowledge, this is the first study aimed at equating or maximizing the external load provided by elastic bands and that provided by the constant resistance (i.e., weight plates) in squat exercises.

4.1 Methods

This descriptive, double-blinded study with a repeated-measures design compared the use of elastic bands and weight plates in six different conditions of the squat exercise in healthy, physically active males. The numbers of repetitions and kilograms were measured as parameters of the external load (Halson, 2014). In addition, we analyzed the rate of perceived exertion, systolic and diastolic blood pressure, and heart rate as measurements of the internal load (Colado et al., 2012; Halson, 2014; Iglesias-Soler et al., 2015; Iversen et al., 2017; Maté-Muñoz et al., 2015; Robertson et al., 2003).

The six squat conditions were [1] 10 repetition maximum (corresponding to approximately 75% 1RM) with weight plates (10RMWP) loaded at the standing position (i.e., body standing up straight in standard anatomical position); [2] 5RM with weight plates (5RMWP) loaded at the standing position, which load corresponded to approximately 85% 1RM; [3] 9 submaximal repetitions with weight plates (9RSMWP) loaded at the standing position with the same weight as used for the 10RMWP condition; [4] 10 submaximal repetitions using elastic bands (10REB) to load the bar with the same weight as used in the 10RMWP condition loaded at the standing position; [5] the maximal number of repetitions using elastic bands (XRMEB) with the same weight as used for 10RMWP loaded at the standing position; and [6] the maximal number of repetitions with the same weight as used for 10RMWP but using elastic bands to load the bar with the desired weight immediately above the estimated knee sticking point (XRMEBSP), namely at the 110º knee joint angle, being the 180º knee joint angle fully extended knees (Escamilla et al., 2001; Hales et al., 2009; Kompf & Arandjelović, 2017; Van den Tillaar et al., 2014). The term "weight plates" was chosen over "free weights" due to the fixed nature of the Smith machine.

All measurements were conducted at the Optometric Clinic *Fundació Lluís Alcanyís* at the University of Valencia (Spain). We conducted the study in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki), and permission was provided by the University of Valencia's Ethics Committee on Human Research (H1499867368458). All participants voluntarily agreed to participate and were free to withdraw from the study at any time. Each participant was informed of the benefits and risks of injury derived from the investigation before signing an institutionally approved informed consent form.

4.1.1 Participants

A sample size of 19 participants was determined by a power analysis (G*Power 3.0; Faul et al., 2007) assuming an α of 0.05, a power level of 0.8, an effect size of f(V) = 0.87, and a nonsphericity correction of $\varepsilon = 1$. Prior to the study, all subjects received a full physical examination to assess their posture and squat technique and confirm their validity for the study. Inclusion criteria were 1) younger than 40 years old, 2) experience in strength training for at least six months and performing at least two days per week of lower limb training including squats, and 3) no musculoskeletal health issues.

As a result, of the 30 recruited subjects, only 20 met the criteria and voluntarily participated in this study. All subjects were physically active males (25.50 ± 5.26 years old, 95% confidence interval [23.04–27.96]; body mass index: 24.09 ± 2.06 kilograms/meters^2, 95% confidence interval [23.13–25.05]; body fat: 10.16 ± 2.23%, 95% confidence interval [9.12–11.20]; Squat 1RM: 127.10 ± 24.10 kilograms, 95% confidence interval [115.82–138.38]; ratio 1RM-bodyweight (relative strength): 1.70 ± 0.36, 95% confidence interval

[1.55–1.85]). All participants were instructed to avoid alcohol consumption and strenuous exercise 24 hours before all sessions. They were asked to consume their typical diet, drink one liter of water, sleep for at least eight hours, and not consume stimulants, take supplements, or smoke before the trial. Additionally, water intake was controlled throughout the entire trial, allowing subjects to drink *ad libitum* to maintain proper hydration and performance (Kenefick, 2018).

4.1.2 Procedures

The exercise protocol consisted of three sessions: two for familiarization and assessment and one for the experimental trial. All data were collected in a thermoneutral environment (~22ºC and ~60% humidity) and at the same time of day to avoid diurnal variations in subjects' performance (Sundstrup et al., 2012). All measurements were taken by the same researchers and were always conducted in the same laboratory. The physiological measurements were conducted in an adjacent space separated from the Smith machine by a partition screen to blind the researcher. The subjects were instructed not to look at the Smith machine before performing each condition. Participants rested in the aforementioned separated space while listening to music with headphones to avoid hearing audible information about the next condition. Constant feedback was given, and two trained spotters stood on each side of the bar to ensure proper execution and to encourage maximum effort.

In the first session, participants signed the consent form, filled in the demographic questionnaire and guarantee of data confidentiality, and underwent a physical examination. Height (meters), weight (kilograms), and body fat percentage were obtained with a height rod and a bioelectrical impedance scale Body Composition Analyzer BF-350 (Tanita, Corporation, Tokyo, Japan). Body mass index was calculated as body mass [kilograms] / (height [meters])^2. Thereafter and before the warm-up, measurements of the pertinent knee angle were taken (Figures 1 and 12), and a mark was made on the Smith machine to identify the height of the bar when the subject was at this point of the range of motion. At this point, participants were instructed in how to perform the squats at the correct pace and how to use the OMNI-RES scales of perceived exertion with weight plates (Robertson et al., 2003) and elastic bands (Colado et al., 2012). Previous studies can be consulted for further details regarding how to apply the rate of perceived exertion scales (Maté-Muñoz et al., 2015; Naclerio & Larumbe-Zabala, 2017). The standardized warm-up included joint mobility, bodyweight exercises, jogging, and dynamic stretching. After the warm-up and before the 1RM testing, participants performed three sets of squats using the Smith machine: first, 20 repetitions without additional weight and then two more sets of 15 and 12 submaximal repetitions; weights for the last two sets were selected according to participants' perceived 20RM and 15RM. Finally, maximum weights were assessed through a fatigue test with submaximal loads as previously reported in the literature (Reynolds et al., 2006). Participants performed the maximal number of repetitions with a weight selected based on the previous sets. If a participant performed more than 12 repetitions or less than 8 repetitions, another set with an altered weight was performed, allowing at least a five-minute rest; more time was permitted depending on the participants' perceived level of recovery (Laurent et al., 2011). Data were registered and used to obtain the load for 1RM using O'Connor or Brzycki formulas (Reynolds et al., 2006). Percentages were calculated for 75% 1RM and 85% 1RM.

A second session was used to ensure the validity of the maximum loads, knee angle measurements, and 75 and 85% 1RM obtained during the first session, while participants gained further experience in using the rate of perceived exertion scales. Subjects performed maximal and submaximal sets in random order (https://www.random.org/lists/) with different loads using elastic bands and weight plates. If the participant was able to perform more than 10 repetitions with weight plates at 75% 1RM or more than five repetitions at 85% 1RM, weights were adjusted to match the requirements.

The third session was targeted to evaluate all dependent variables. First, participants underwent a physical examination to determine resting values for each physiological variable. After the warm-up, each of the six conditions was performed in a random (https://www.random.org/lists/) and balanced order. For Condition 6, the bar was placed at the height corresponding to the point of the range of motion at which the subject presented a 110º knee joint angle (i.e., the sticking point), and as many bands as needed were attached to the bar to achieve the 10RM load. Thereafter, a researcher placed the bar at the height corresponding to the participant's standing position (i.e., 180º of knee joint angle), and the subject performed the set. All dependent variables were measured immediately after performing each condition in the following order: rate of perceived exertion, heart rate, and blood pressure (systolic and diastolic). The number of repetitions performed and the kilograms were also recorded at that time if the condition required it. At least a five-minute rest was given between sets, and more time was permitted depending on the participants' perceived level of recovery (Laurent et al., 2011).

Squat exercise

A high-bar back squat (bar placed across the shoulder on the trapezius slightly above the posterior aspect of the deltoids; Gene-Morales, Flandez, et al., 2020; Schoenfeld, 2010b; Vigotsky et al., 2019) to a parallel depth (Bryanton et al., 2012; Clark et al., 2012; Gene-Morales, Flandez, et al., 2020; Saeterbakken et al., 2016) was performed. The stance width was established for each subject between the hips and shoulder (Gene-Morales, Flandez, et al., 2020; Schoenfeld, 2010b). Shoes were used, but no weightlifting belts or knee wraps were permitted (Clark et al., 2012; Vigotsky et al., 2019).

To standardize the range of motion, sticking point, and pace of movement, a goniometer, tactile markers, and metronome were used. Depth was adjusted with a horizontal elastic band when the femur (marked by the line from the great trochanter to the knee lateral condyle) of each participant was parallel to the ground. Participants had to touch the band (midthigh) in every repetition before starting the concentric phase. Moreover, a crossline auto laser level was fixated with a tripod (LZR6TP, Black and Decker, New Britain, CT, USA) and was used as visual feedback in connection with the requested joint positioning during exercise. The tempo consisted of an inhalation-coordinated eccentric phase lasting two seconds (Schoenfeld, 2010b) with a pause of one second at the lowest point (femur parallel to the ground) and an exhalation-coordinated maximum speed concentric phase (four seconds for a complete squat). The pause at the transition from the eccentric to the concentric phase was designed to dissipate stored elastic energy within the muscles (Aboodarda et al., 2013).

Blood pressure and heart rate

Cardiac measurements were performed immediately after finishing each condition using a digital automatic blood pressure monitor (M6W HEM-7213-E [V], Omron Healthcare, Kyoto, Japan). The intraclass reliability of the instrument was 0.90 for the systolic blood pressure, 0.86 for the diastolic blood pressure, and 0.91 for the heart rate. These values are considered excellent (> 0.80; Fleiss, 1986).

Rating of perceived exertion

The rate of perceived exertion for the overall body was measured immediately after finishing each of the six conditions with the OMNI-RES for weight training (Robertson et al., 2003) and the OMNI-Resistance Exercise Scale of Perceived Exertion for elastic bands (Colado et al., 2012). These scales measure the perceived effort of the overall body (not the active muscles) on a scale from 0 to 10, with 0 being “no effort” and 10 “maximum effort.” The intraclass correlation coefficient of the rate of perceived exertion values given by the subjects when performing at 75 and 85% 1RM in the familiarization and experimental sessions was 0.83, which is considered an excellent value (Fleiss, 1986).

Strength training equipment

A Multipower Smith machine Powerline PSM144X (Body-Solid, Salt Lake City, UT, USA) was loaded with 28 mm cast iron plates (Domyos, Villeneuve-d'Ascq, France) ranging from 0.50 to 20 kilograms or with looped CLX elastic bands (TheraBand, Akron, OH, USA). The barbell weighed 20 kilograms. To measure the load for each condition, a 100-g precision scale model 9179 SV3R (Salter, Manchester, United Kingdom) was used.

4.1.3 Statistical analyses

A repeated-measures design was used to determine systemic variable fluctuations according to perceptual and physical performance variables after the squat exercise protocol. Normality of data distribution was evaluated using the Shapiro-Wilk test, showing a normal Gaussian distribution ($p > 0.05$) except for the rate of perceived exertion ($p < 0.05$). To assess differences between conditions in normally distributed variables, a one-way ANOVA for repeated measurements was used. Where Mauchly’s sphericity assumptions were violated, Greenhouse-Geisser adjustment of the *p*-values was reported. Effect size was evaluated with partial eta squared (ηp^2), where $0.01 < \eta p^2 < 0.06$ constitutes a small effect, $0.06 \leq \eta p^2 \leq 0.14$ constitutes a medium effect, and $\eta p^2 > 0.14$ constitutes a large effect. When differences were detected, post-hoc tests with Bonferroni corrections examined where differences occurred. The magnitude of the paired differences was assessed through Cohen’s effect size. The results (Cohen’s *d* coefficient) were interpreted following the specific scale to training research with negligible ($d < 0.20$), small ($0.20 < d < 0.49$), moderate (0.50 $d < 0.79$), and large ($d \geq 0.80$) effects (Cohen, 1988). Nonparametric Friedman tests identified differences in the rate of perceived exertion between conditions, and when differences were detected, paired Wilcoxon signed ranks tests showed where these differences occurred.

Test-retest reliability of the instruments (blood pressure monitor and rate of perceived exertion scales) was assessed in a subsample of 10 subjects calculating the intraclass correlation coefficient. The intraclass correlation coefficient was interpreted as poor (< 0.40), moderate (0.40–0.59), good (0.60–0.79), or excellent (≥ 0.80; Fleiss, 1986).

Statistical analyses were performed using commercial software IBM SPSS Statistics for Macintosh (Version 26.0, IBM Corp., Armonk, NY, USA). An α of 0.05 was used to determine significance in all cases. All results are reported as mean and standard deviation with confidence intervals at 95%.

4.2 Results

4.2.1 External load

Repeated measurement testing revealed significant differences in the weight used, number of repetitions performed, and reported rate of perceived exertion among the six conditions (weight: $F[5, 95] = 128.82$, $p < 0.001$, $\eta p^2 = 0.87$; number of repetitions: $F[5, 95] = 72.40$, $p < 0.001$, $\eta p^2 = 0.79$; rate of perceived exertion: X^2 $[5] = 64.17$, $p < 0.001$). Table 7 shows the performance variables and rate of perceived exertion results for each of the six squatting conditions.

As Table 7 shows, adding the load for 10RM with elastic bands immediately above the sticking point (Condition 6) resulted in a statistically significant increase of 24.7% in the weight at the standing position compared with 10RM with weight plates (Condition 1: mean difference 23.70 ± 9.45 kilograms, 95% confidence interval [19.27–28.12], $p < 0.001$, $d = 1.15$), surpassing the participants' theoretical 90% 1RM (Figure 12). This weight was also significantly higher compared with 5RM with weight plates (Condition 2: mean difference 11.05 ± 9.02 kilograms, 95% confidence interval [6.83–15.27], $p < 0.001$, $d = 0.51$).

Table 7. External load variable outcomes and rate of perceived exertion of the different squatting conditions.

Condition	Kilograms at the standing position	Number of repetitions	Rate of perceived exertion
1 (10RMWP)	95.95 ± 17.88 [87.58–104.32]	10.00	8.55 ± 0.88[2,3,4,6] [8.14–8.96]
2 (5RMWP)	108.60 ± 20.24* [99.13–118.07]	5.00*	7.75 ± 0.72[1,4,5,6] [7.41–8.09]
3 (9RSMWP)	95.95 ± 17.88 [87.58–104.32]	9.00	7.55 ± 0.99[1,4,5,6] [7.09–8.01]
4 (10REB)	95.95 ± 17.88 [87.58–104.32]	10.00	6.50 ± 1.24* [5.92–7.08]
5 (XRMEB)	95.95 ± 17.88 [87.58–104.32]	18.40 ± 4.86* [16.13–20.67]	8.65 ± 0.93[2,3,4,6] [8.21–9.09]
6 (XRMEBSP)	119.65 ± 22.86* [108.95–130.35]	13.45 ± 3.84 * [11.65–15.5]	9.10 ± 0.55* [8.84–9.36]

Note: 95.95 kilograms, 108.60 kilograms, and 119.65 kilograms corresponded to approximately 75%, 85%, and 94% of participants' 1RM, respectively. A 20-kilogram barbell was used in all the conditions. Values are expressed as mean ± standard deviation [95% confidence interval]. *: statistically significant difference compared to the rest of the conditions. [1, 2, 3, 4, 5, 6]: significant difference with the condition 1, 2, 3, 4, 5, or 6. RMWP: repetition maximum with weight plates. RSMWP: submaximal repetitions with weight plates and with the same weight used for the 10RMWP condition. EB: elastic bands. REB: submaximal repetitions with EB with the same weight as used for the 10RMWP condition. XRMEB: repetitions to failure with elastic bands with the same weight as used for the 10RMWP condition. XRMEBSP: repetitions to failure with EB and loaded with the same weight as used for the 10RMWP condition and placed immediately above the knee sticking point.

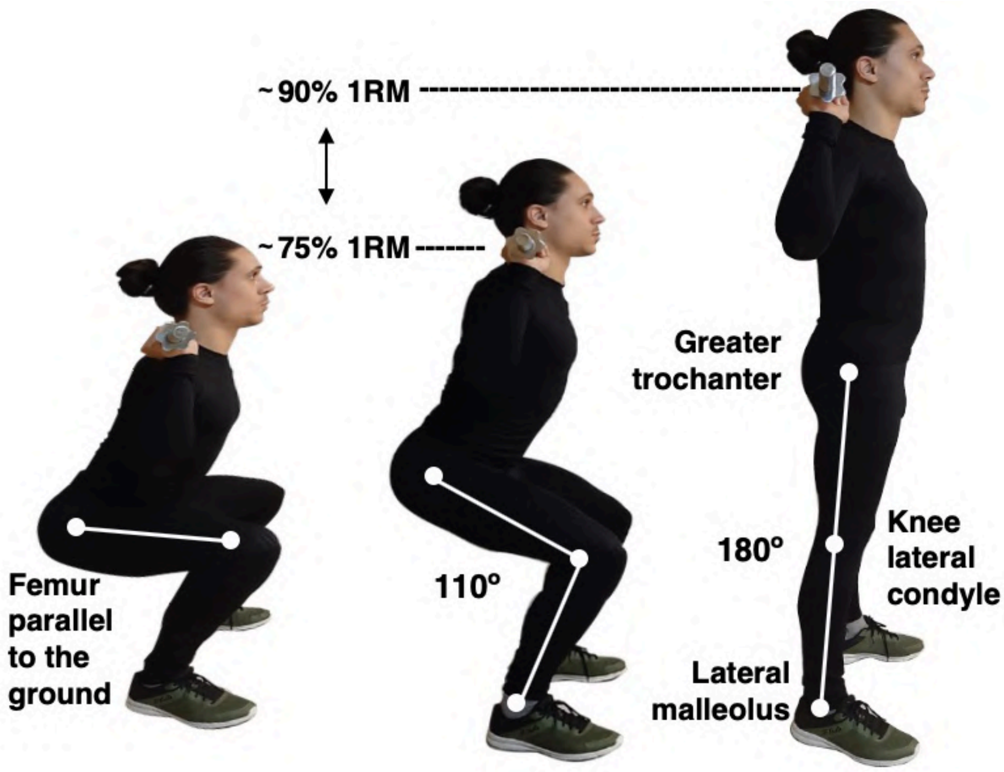

Figure 12. Relevant points of the squat performance in Condition 6. The lowest position (left), the position immediately above the estimated sticking point (middle), and the standing position (right) are pictured. Anatomical points used to measure the knee angle are identified. Significant differences ($p < 0.001$, $d = 1.15$) between the relative load (percentages of one repetition maximum [1RM]) in the middle and right pictures were found. Both 1RM percentages are rounded values, with ~75% 1RM being 95.95 ± 17.88 kilograms [87.58–104.32] and ~90% 1RM being 119.65 ± 22.86 kilograms [108.9–130.35].

Furthermore, while participants used significantly more weight, they were able to perform on average 3.45 ± 3.84 more repetitions (95% confidence interval [1.65–5.25]) in Condition 6 compared with Condition 1 (10RM with weight plates: $p = 0.001$, $d = 1.27$) and 8.45 ± 3.85 more repetitions (95% confidence interval [6.65–10.24]) than in Condition 2 (5RM with weight plates: $p < 0.001$, $d = 3.10$). Concerning the comparison between the maximal effort at a 10RM load at the standing position with elastic bands (Condition 5) and the 10RM with weight plates (Condition 1), participants performed on average 8.40 ± 4.86 more repetitions (95% confidence interval [6.13–10.67]) in the condition with elastic bands ($p < 0.001$, $d = 2.44$).

4.2.2 Internal load

Concerning the rate of perceived exertion (see Table 7), nonsignificant differences ($p > 0.05$) were observed between performing 10RM with weight plates (Condition 1) and performing approximately 18RM with elastic bands (Condition 5). The lowest values were found in the condition comprising a submaximal effort of 10 repetitions at a 10RM load with elastic bands (Condition 4) with significant differences from the rest of the conditions (Condition 1: $p < 0.001$, $d = 1.91$; Condition 2: $p = 0.001$, $d = 1.23$; Condition 3: $p < 0.05$, $d = 0.94$; Condition 5: $p < 0.001$, $d = 1.96$; Condition 6: $p < 0.001$, $d = 2.71$). The condition consisting of a maximal effort with a 10RM load added immediately above the sticking point with elastic bands (Condition 6) resulted in the highest rate of perceived exertion with significant differences compared to the rest of the conditions (Condition 1: $p < 0.05$, $d = 0.75$; Condition 2: $p < 0.001$, $d = 2.11$; Condition 3: $p < 0.001$, $d = 1.93$; Condition 5: $p < 0.05$, $d = 0.59$).

Repeated measures testing indicated a significant blood pressure and heart rate increase after each condition compared with baseline values except for the diastolic blood pressure after Conditions 4 ($p = 0.075$) and 5 ($p = 0.085$). However, post-hoc analyses showed no significant differences between the six conditions in systolic or diastolic blood pressure. Regarding the heart rate, Condition 6 did not show significant differences from almost the rest of the conditions. The smallest increases were observed after a maximal effort of 5RM with weight plates (Condition 2: +28.00 beats per minute, 95% confidence interval [18.04–37.95]), showing significant differences from the rest of the conditions. On the other hand, a maximal effort of approximately 18 repetitions at a 10RM load added at standing position using elastic bands (Condition 5) resulted in the highest heart rate, showing significant differences from all the conditions performed with weight plates and only a trend when compared with Condition 1 (Condition 1: $p = 0.05$, $d = 0.29$; Condition 2: $p < 0.001$, $d = 0.92$; Condition 3: $p < 0.05$, $d = 0.35$) and with the submaximal 10 repetitions with elastic bands (Condition 4: $p < 0.01$, $d = 0.53$). Table 8 shows the cardiovascular variable results after each condition and repeated measures testing concerning resting values; differences between conditions are also identified.

Table 8. Internal load outcomes of the different squatting conditions.

Condition	Systolic blood pressure (mmHg)	Diastolic blood pressure (mmHg)	Heart rate (bpm)
Resting	126.65 ± 10.65* [122.30–131.05]	68.30 ± 6.08[1, 2, 3, 6] [65.65–70.90]	64.05 ± 10.98* [58.91–69.19]
1 (10RMWP)	148.05 ± 20.39 [139.45–157.85]	74.25 ± 8.72 [70.35–78.10]	105.45 ± 16.35[2, 4] [97.80–113.10]
Δ%	+16.90	+8.71	+64.64
Cohen's *d*	1.32	0.79	2.97
2 (5RMWP)	144.00 ± 16.09 [136.95–151.35]	73.55 ± 8.79 [69.85–77.45]	92.05 ± 18.48* [83.40–100.70]
Δ%	+13.70	+7.69	+43.72
Cohen's *d*	1.27	0.69	1.84
3 (9RSMWP)	146.25 ± 23.33 [137.00–156.25]	74.00 ± 7.89 [70.60–77.30]	104.20 ± 17.40[2,5] [96.06–112.34]
Δ%	+15.48	+8.35	+62.69
Cohen's *d*	1.08	0.81	2.76
4 (10REB)	146.40 ± 13.39 [140.45–152.05]	72.70 ± 9.17 [68.85–76.80]	100.60 ± 16.44[1 ,2, 5] [92.91–108.29]
Δ%	+15.59	+6.44	+57.06
Cohen's *d*	1.63	0.57	2.61
5 (XRMEB)	144.55 ± 18.40 [136.95–152.75]	72.35 ± 10.06 [68.10–76.90]	111.35 ± 23.25[1, 2, 3, 4] [100.47–122.23]
Δ%	+14.13	+5.93	+73.85
Cohen's *d*	1.19	0.49	2.60
6 (XRMEBSP)	146.45 ± 19.60 [137.90–154.50]	75.35 ± 10.63 [70.60–80.05]	107.85 ± 14.63[2] [101.00–114.70]
Δ%	+15.63	+10.32	+68.38
Cohen's *d*	1.26	0.81	3.39

Note: Repeated measures testing with respect to baseline values is displayed with the percentage of variation (Δ%) and effect size (Cohen's d unbiased; $d_{unb} < 0.50$ small, $0.50 \leq d_{unb} \leq 0.79$ moderate, and $d_{unb} \geq 0.80$ large). Values are expressed as mean ± standard deviation [95% confidence interval]. *: statistically significant difference compared to all other conditions. [1, 2, 3, 4, 5, 6]: significant difference compared to conditions 1, 2, 3, 4, 5, or 6. RMWP: repetition maximum with weight plates. RSMWP: submaximal repetitions with weight plates and with the same load used for the 10RMWP condition. EB: elastic bands. REB: submaximal repetitions with EB and the same weight as used for the 10RMWP condition. XRMEB: repetitions to failure with elastic bands with the same weight as used for the 10RMWP condition. XRMEBSP: repetitions to failure with EB and the same weight as used for 10RMWP condition and placed immediately above the knee sticking point.

4.3 Discussion

This study compared the physical performance, perceived effort rate, and cardiovascular responses to a squat protocol using different training devices (elastic bands or weight plates), and with different reference points to charge the total load when elastic bands were used (i.e., the initial position of the movement versus the position immediately above the sticking point). To the best of our knowledge, this is the first study to analyze the performance in a squat movement with the load added immediately above the sticking point with elastic bands and thus may have important implications for exercise prescription.

Consistent with the hypothesis, the main finding was that compared with the 10RM with weight plates (Condition 1), adding the load for 10RM immediately above the sticking point with elastic bands (Condition 6) permitted participants to perform approximately three more repetitions with more weight (25% more kilograms at the standing position; see Table 7) during at least 70º of knee movement (from 110º to 180º at fully extended knees; see Figure 12). This condition also permitted participants to perform approximately eight more repetitions with 10% more weight at the standing position than in 5RM with weight plates (Condition 2; see Table 7). Furthermore, physiological measurements of the internal load (blood pressure and heart rate) were not significantly higher than almost the rest of the conditions (see Table 8) even though participants perceived Condition 6 as the most demanding. These findings highlight the usefulness of this new method of applying the elastic resistance in squats to achieve more repetitions while using more weight and provoking similar physiological responses. Loading the elastic resistance immediately above the squat sticking point compared with adding the load in the standing position could induce higher muscle fiber recruitment due to using more weight over more repetitions, which may lead to better chronic adaptations (Soria-Gila et al., 2015). Supporting this fact, increments in load for the same squat variation have been shown to produce a positive impact on muscle activation (Clark et al., 2012). Additionally, developing muscle strength is closely related to greater force application, longer duration of muscle tension, and a greater total amount of work (Aboodarda et al., 2013; Bryanton et al., 2012; Schoenfeld, 2010a, 2011).

Concerning the maximal effort adding the load for 10RM at the standing position with elastic bands (Condition 5), participants performed approximately eight more repetitions until exhaustion than in 10RM with weight plates (Condition 1). Condition 5 was not perceived as more exhausting and did not show blood pressure differences from the aforementioned 10RM with weight plates. However, Condition 5 provoked a slightly higher heart rate compared with Condition 1 with a small effect size (Cohen's *d*) of 0.29. This fact confirms that in comparison with weight plates, adding the same load at the standing position with elastic allows for a larger time under tension while maintaining similar internal load values. A larger time under tension has been shown to increase glycolysis metabolism and may promote greater muscle adaptations by stimulating delayed muscle protein synthesis at 24 to 30 hours of recovery (Burd et al., 2012).

In the submaximal conditions (Conditions 3 and 4; one more repetition with elastic bands and the same weight at the standing position), elastic bands provoked comparable blood pressure and heart rate responses to weight plates (see Table 8). Conversely, 10 repetitions with the load for 10RM added at the standing position with elastic bands (Condition 4) was perceived as the least demanding condition (see Table 7). This fact is probably due to this condition having the minimum total amount of work, which total is obtained by multiplying weight used by repetitions performed (McLester et al., 2000; Schoenfeld, 2011). The similarities in the cardiovascular outcomes may be associated with the comparable number of repetitions as explained further below (see Section 4.2.2).

4.3.1 A general approach to the use of elastic bands in squats

Bearing in mind the central target of this research, it is worth discussing the potential use of elastic bands as a device to load the bar in squats. Within a parallel squat, muscle activation is greatest in the last phase of the descent and the first phase of the ascent (Clark et al., 2012). Knee extensors' effort increases when the squat depth increases, and higher activity in hip extensors and ankle plantar flexors occurs when the barbell load increases (Bryanton et al., 2012). Since elastic bands provide less weight in the lower part of the range of motion and more in the upper part (V. Andersen et al., 2016), elastic bands could optimally activate the neuromuscular system through the entire range of motion (Saeterbakken et al., 2014; Walker et al., 2011), moreover adding the load immediately above the sticking point. From a practical perspective, squatting with elastic bands could allow the athlete to go down to the deepest point of the range of motion with less mechanical stress acting against the knees in the sticking region (Kompf & Arandjelović, 2016; Schoenfeld, 2010b; Vigotsky et al., 2019). Immediately after this mechanically disadvantageous range of motion, the muscles of the hips and ankles would be enhanced as a result of the increment in the weight provided by the elastic bands due to the elongation coefficient (Bryanton et al., 2012; Kompf & Arandjelović, 2017; Saeterbakken et al., 2016). Combining all these facts from a biomechanical perspective suggests that in similar conditions of load, elastic bands are an appropriate device to load the bar in squats with no need to use weight plates.

Nevertheless, most previous research has used elastic bands with a lower tensile force or in combination with higher loads of constant resistance devices (V. Andersen et al., 2015; Iversen et al., 2017; Saeterbakken et al., 2014, 2016). Only some studies are in line with our procedures and have used elastic bands to achieve similar or even higher external resistance compared to constant resistance devices (Aboodarda et al., 2013; L. L. Andersen et al., 2010; V. Andersen et al., 2016; Colado et al., 2010; Colado & Triplett, 2008). It is important to note that in our study the weight of the barbell should be considered as constant resistance. It represented approximately 20% of the total load in Conditions 4 and 5 and less than 17% in Condition 6. Our findings, with the new strategy of adding the load above the sticking point, support the use of elastic bands to achieve similar or even higher loads than constant resistance devices. However, our results should be interpreted cautiously and be compared with the existing literature.

4.3.2 Applying the pertinent load after the mechanical disadvantage

As far as we are aware, this is the first study to describe the acute effects of applying the load at two different points of the range of motion in a squat (i.e., at the initial position of the exercise versus immediately above the sticking point) using elastic bands. Therefore, our findings with respect to the increments in the external load when adding the elastic resistance immediately above the sticking point are difficult to compare with the existing literature. Only a few authors have similarly used elastic bands (Aboodarda et al., 2013; Page et al., 2015; Treiber et al., 1998). For instance, Page et al. (2015) used elastic bands initially elongated 15 cm beyond their original length to perform different upper body and trunk exercises. This resulted in greater improvements in the serve of racquetball players than their usual training program did. Similarly, Aboodarda et al. (2013) shortened the elastic bands by 30% of their resting length to perform 8RM of a biceps curl on anatomical position and identified higher muscle activation levels than from nonshortened elastic bands or dumbbells at the end of the concentric phase and the beginning of the eccentric phase. Aboodarda et al.'s results (2013) show how the reduction of the basal length of the elastic bands at the beginning of the movement is another way to increase the load above the sticking point. As occurred in our study, this specific strategy allows for an increase in the kilograms moved among the more mechanically efficient region of the movement and thus an increase in muscle activation in comparison to the habitual use of the elastic bands (Aboodarda et al., 2013; Behm & Colado, 2012, 2013; Clark et al., 2012). It also reduces differences in muscle activation compared to constant resistance in this region of the range of motion (Aboodarda et al., 2013). This strategy leads to an increase in muscle activation levels due to the possibility of using more weight throughout the more mechanically effective region of the movement in both the concentric and eccentric phases (Kompf & Arandjelović, 2016, 2017; Saeterbakken et al., 2016) as our study shows. It is also important to note that we found that five fewer repetitions were performed when the load was added immediately above the sticking point using elastic bands (Condition 6) compared with when the load was added at the standing position using elastic bands (Condition 5; see Table 7). On the other hand, Aboodarda et al. (2013) found no difference in the number of repetitions between performing with shortened or nonshortened elastic bands. This fact may be due to the difference in loads between both methods. Aboodarda et al. (2013) only encountered significant differences in the load at the first degrees of the concentric phase and the final segments of the eccentric phase of the biceps curl (i.e., the first degrees of elbow flexion in the anatomical position). In contrast, we found significantly higher loads in the last degrees of the concentric phase and at the start of the eccentric phase of the squat exercise. These differences could be explained through the approach to the use of elastic bands. Our procedures are not based on elongating or shortening the elastic bands depending on their basal length but on adding the elastic resistance at different heights to overcome the sticking region depending on the athlete's biomechanics. In this regard, 110º of knee joint angle (i.e., 70º of knee flexion or a tight angle relative to the ground of 20º) seems to be a good point to add the load with the elastic bands.

From an applied perspective, our study is in agreement with previous research on the possibility of lifting more weight when elastic bands are combined with the traditional training with weight plates. Ghigiarelli et al. (2009) and Joy et al. (2016) obtained positive increases in force production when implementing elastic bands in combination with traditional constant resistance during exercises performed with concentric movements as quickly as possible. These chronic positive neuromuscular adaptations were probably instigated by using more weight with the elastic bands, overcoming the sticking point in each set of the resistance training program (Kompf & Arandjelović, 2016, 2017; Soria-Gila et al., 2015). According to our results in terms of squatting exclusively using elastic bands, we can state that participants can load 25% more weight at standing position (Condition 6) than the weight used for a 10RM set with traditional weight plates performed at a controlled pace of movement (Condition 1; see Table 7). This could mean that it is possible to add 25% more weight directly and easily at the standing position with no need to measure the sticking point before beginning the exercise to add the pertinent weight. It can also be noted that it may be possible to add the extra weight with elastic bands to the traditional weight plates load to obtain these benefits during a 10RM set performed with a controlled pace of movement as previously suggested in the literature (Joy et al., 2016). However, we have not analyzed this condition, and the final number of repetitions performed may vary.

4.3.3 Internal load outcomes

In cardiovascular terms, our results are in accordance with previous research that ensures heart rate and blood pressure increments after high-intensity squat exercise, with greater increases after the sets with a higher number of repetitions (Iglesias-Soler et al., 2015). Cardiovascular responses seemed to be influenced by the volume rather than the weight or the material used.

Regarding the rate of perceived exertion (see Table 7), elastic band conditions were perceived as less demanding than weight plate conditions when performing at similar loads (Conditions 3 and 4). Furthermore, performing approximately 18RM with elastic bands was not perceived as more demanding than performing 10RM with weight plates (Conditions 1 and 5, respectively). One possible explanation for the participants perceiving Condition 6 (load added immediately above the sticking point) as the most demanding condition could be the higher amount of total work (higher volume of repetitions performed with more weight). In accordance with our results, Sundstrup et al. (2012) reported a lower rate of perceived exertion after 3RM of lateral raises with elastic bands (4.54 ± 2.09) than after repetitions to failure at an approximately 15RM load also with elastic bands (7.58 ± 2.02). Our findings are in contrast with some studies that did not find significant differences between performing at similar effort levels with elastic or constant resistance (L. L. Andersen et al., 2010; Iversen et al., 2017). These differences may be due to using the rate of perceived exertion scales for the active muscles or, in contrast, for the overall body (Colado et al., 2014).

4.3.4 Limitations

Even though all the procedures were carefully supervised and all statistical parameters accurately and positively tested during the collection of data, some specific issues should be listed as potential sources of bias.

First, the variability between exercise protocols makes it difficult to compare results with the available literature, which limits the generalizability of our findings. First, the loads obtained in our study for 5RM and 10RM (Table 7) are consistent with the percentages (V. Andersen et al., 2015; Reynolds et al., 2006; Shimano et al., 2006; Walker et al., 2011) and kilograms (Joy et al., 2016) used by some studies with varied samples. On the other hand, some research assessing free barbell squats has reported lower average loads (V. Andersen et al., 2016; Bryanton et al., 2012; Iversen et al., 2017; Saeterbakken et al., 2016), and one study showed greater loads (Vigotsky et al., 2019). These differences could be explained through the variability in the sample characteristics and the disparities of performing the squat using a Smith machine or a free barbell. In this respect, an increment of 14 to 23 kilograms has been reported when using the Smith machine due to the more stable conditions (Behm & Colado, 2012, 2013; Clark et al., 2012). Additionally, it is worth mentioning that our sample consisted only of males.

Finally, as previously stated, in the absence of more specific scientific evidence obtained with medium- and long-term intervention studies, our comments are basic suggestions as to whether adaptation to applying the total weight using elastic bands immediately above the sticking point could chronically result in even higher levels of central neural activation, muscle hypertrophy, and increased strength development.

4.4 Conclusion

As far as we are aware, this was the first study that applied the pertinent weight immediately above the sticking point instead of at the standing position using elastic bands. Therefore, and considering the positive results obtained, future research applying this methodology is guaranteed (see Chapter 6).

In summary, our findings show that depending on how the bands are applied (i.e., immediately above the sticking point or at the participants' standing position), squatting with elastic bands 1) allows participants to use more weight after the sticking region than squatting only with weight plates; 2) facilitates a higher number of repetitions, which could permit a greater time of muscle activity or time under tension (i.e., how long a muscle is under strain during a set); and 3) optimizes cardiovascular responses and perceived effort rating. This confirms the second hypothesis of the present doctoral thesis.

The evidence presented in this study highlights the possible practical applications of elastic bands for subjects who need to exercise with a high percentage of 1RM with no need to use weight plates to load the bar as opposed to previous literature that was not able to obtain enough weight with elastic bands. Additionally, those athletes who want to avoid high cardiovascular and perceptual stress during resistance training without reducing muscular demands could also safely use elastic bands in different ways. In conclusion, elastic bands could reduce cardiovascular and perceptual stress depending on if they are attached to the bar at the participants' standing position or just above the sticking point. Elastic bands are presented as a solid option to perform resistance training at high percentages of 1RM and volumes, with no need to combine elastic bands with weight plates.

This chapter compared the performance outcomes of using elastic bands versus weight plates to load the bar in squats, with positive results for the elastic bands. Therefore, the next study (see Chapter 5) evaluated the potential differences in ocular and cardiovascular parameters between using elastic bands and weight plates to load the bar in squats.

Chapter 5. The potential use of elastic bands to provoke conservative ocular and cardiovascular responses

Effects of squatting with elastic bands or conventional resistance-training equipment at different effort levels on the postexercise intraocular pressure of healthy men

5. The potential use of elastic bands to provoke conservative ocular and cardiovascular responses

The third study of the present doctoral thesis (see Chapter 4; Gene-Morales, Gené-Sampedro, et al., 2020) shows positive results for elastic bands compared to weight plates in terms of performance (more repetitions with more weight after the sticking point), cardiovascular (similar cardiovascular responses after performing more repetitions with more weight), and perceptual responses (similar perceived effort after performing more repetitions). Therefore, a health approach to the use of elastic bands was employed for this fourth article.

Concerning ocular health, several studies examined intraocular pressure responses to dynamic resistance training exercises, producing controversial results (see Section 1.2.1). The first study of the present doctoral thesis (see Chapter 2; Gene-Morales et al., 2021) showed that intraocular pressure of healthy gymnasts is reduced after an acrobatic gymnastics session, and central corneal thickness remains unchanged. Therefore, the question arises whether performing squats at different intensities could significantly modify central corneal thickness. Additionally, sex and baseline intraocular pressure were encountered as significant predictors of the intraocular pressure variations produced in Chapter 2. Bearing in mind the prediction potential of sex and baseline intraocular pressure, physically active males with baseline intraocular pressure below or equal to 21 mmHg were selected for this fourth study of the compendium.

Considering the gap of knowledge that still exists concerning intraocular pressure variations due to resistance training and the relevance of mean arterial blood pressure and pulse pressure in cardiovascular health, the study of different materials commonly used for resistance training proves necessary to increase the scientific body of knowledge in this regard. As far as we are aware, this is the first study to compare ocular and cardiovascular acute adaptations to squatting using elastic bands or weight plates to load the bar. More specifically, this fourth study of the compendium composing the present doctoral thesis analyzed the effects of squatting using elastic bands to load the bar on parameters related to ocular (intraocular pressure, mean ocular perfusion pressure, and central corneal thickness) and cardiovascular health (mean brachial arterial blood pressure and pulse pressure) and compared the results with the use of weight plates to load the bar.

5.1 Methods

This quasiexperimental study assessed the changes in ocular and cardiovascular health-related parameters after participants performed guided squats using a Smith machine considering the use of weight plates or elastic bands to load the bar and maximal or submaximal efforts. Besides the main variables (intraocular pressure and mean ocular perfusion pressure), the central corneal thickness was measured to assess whether this parameter may condition intraocular pressure behavior (Gene-Morales et al., 2021; Wylęgała, 2016). The rate of perceived exertion, heart rate, mean brachial arterial blood pressure, and pulse pressure were used to characterize the cardiovascular adaptations to the exercise (Halson, 2014). The four squat sets were as follows:

Sets using weight plates: [1] maximum number of repetitions with 75% 1RM; [2] nine repetitions (submaximal) with 75% 1RM.

Sets using elastic bands: [3] maximum number of repetitions with 75% 1RM; [4] 10 repetitions (submaximal) with 75% 1RM.

A percentage of 1RM commonly employed in resistance training (75% 1RM) was used (Kraemer et al., 2002; Schoenfeld, 2010a). The pertinent weight was added to the bar either with weight plates (28-millimeter cast iron plates from 0.50 to 20 kilograms, Domyos, Villeneuve-d'Ascq, France) or elastic bands (looped CLX elastic bands, TheraBand, Akron, OH, USA) at each subject's standing position. A researcher weighed the bar at this point using a 100-gram precision scale (9179 SV3R, Salter, Manchester, United Kingdom) to ensure the weight for each set with elastic bands. Repetitions for the submaximal sets (Sets 2 and 4) were established at 9 with weight plates and 10 with elastic bands due to observing that subjects could perform 10 or more repetitions with weight plates and many more than 10 repetitions with elastic bands in the pilot studies.

5.1.1 Participants

A sample size of 19 participants was determined by a power analysis (G*Power 3.0; Faul et al., 2007) assuming an α of 0.05, a power level of 0.80, an effect size of f(V) = 0.87 as obtained in the pilot studies, and a nonsphericity correction of ε = 1. Inclusion criteria were 1) younger than 40 years, 2) experience with strength training for at least six months and performing at least two days per week of lower limb training including squats, 3) no musculoskeletal health issues, 4) normal visual health, and 5) no history of ocular disease or surgery. All participants had a baseline intraocular ≤ 21 mmHg, systolic blood pressure between 90 and 140 mmHg, diastolic blood pressure between 60 and 90 mmHg, and pulse pressure ≤ 65 mmHg, excluding possible cardiovascular and ocular disorders (Cantor et al., 2018; Glasser et al., 2014).

As a result, of the 25 recruited, only 20 physically active males met the criteria and voluntarily participated in this study (mean age: 25.55 ± 4.75 years, 95% confidence interval [23.84–28.00]; body mass: 75.67 ± 9.02 kilograms, 95% confidence interval [71.45–79.89]; body mass index: 24.04 ± 2.11 kilograms/meter^2, 95% confidence interval [23.20–25.08]; body fat: 10.19 ± 2.29%, 95% confidence interval [9.32–11.38]; squat 1RM: 126.53 ± 24.62 kilograms, 95% confidence interval [116.32–138.26]; ratio 1RM-bodyweight (relative strength): 1.68 ± 0.35, 95% confidence interval [1.53–1.84]). All participants were instructed to avoid alcohol consumption and vigorous exercise for 24 hours before any of the sessions. They were asked to sleep for at least eight hours, not to consume stimulants or smoke, not to drink more than one liter of liquids (McMonnies, 2016), and not to perform prolonged near-vision tasks in the three hours before the trials (Vera, Jiménez, et al., 2017).

5.1.2 Procedures

All measurements were conducted in the same laboratory by the same researchers (one optometrist and two sport scientists) at the optometric clinic *Fundació Lluís Alcanyís* at the University of Valencia (Spain). All data were collected in a thermoneutral environment (~22ºC and ~60% humidity), under the same lighting and between 10:00 and 13:00 hours since the intraocular pressure is more stable within this time period (Wylęgała, 2016). One session for assessment and familiarization and one experimental trial to evaluate all dependent variables were conducted separated by 48 hours. Each session lasted approximately 90 minutes.

In the familiarization session, the participants signed the consent form and filled in the demographic questionnaire and guarantee of data confidentiality. They also underwent a physical and visual examination to ensure they complied with the inclusion criteria and to assess their squat technique. Anthropometric measurements were obtained with a height rod (IP0955, Invicta Plastics Limited, Leicester, England) and a bioelectrical impedance scale (Body Composition Analyzer BF-350, Tanita Corporation, Tokyo, Japan). Body mass index was calculated as body mass [kilograms] / (height [meters])^2. At this point, the standardized warm-up was started, including joint mobility, bodyweight exercises (including squats), jogging, and dynamic stretching. As a part of the specific warm-up, participants were instructed on how to perform the squats at the correct movement tempo and how to use the rate of perceived exertion scales (Colado et al., 2012; Robertson et al., 2003). After the warm-up, participants performed the 1RM testing. Before the testing, three approximation sets were performed: First, participants completed one set of 20 repetitions without additional weight (the bar weighed 20 kilograms) and then two more sets of 15 and 12 submaximal repetitions out of 20 and 15 maximum repetitions, respectively. Loads for these submaximal sets were selected according to the participant's self-perception and researcher experience. Finally, a fatigue test with submaximal loads using weight plates was conducted at the study-specific squat tempo. This procedure consists of performing between 8 and 12 maximal repetitions and introducing the repetitions performed and the weight used in a formula (Brzycki, 1993; do Nascimento et al., 2007; O'Connor et al., 1989; Reynolds et al., 2006). If a participant performed more than 12 or less than 8 repetitions, the weight was modified, and another set was performed. O'Connor or Brzycki formulas were used to obtaining the load for 1RM. After appropriate rest, the 1RM value obtained in the formula was tested and adjusted if necessary. Kilograms were calculated for 75% 1RM. At least a five-minute rest was allowed between sets; more time was permitted depending on the participants' perceived level of recovery (Laurent et al., 2011).

At the beginning of the second session, baseline measurements of each variable were taken. After the warm-up, the sets were performed in random order. The order of the conditions was randomized using online software (https://www.random.org/lists/). Immediately after the exercise, the researcher in charge recorded the number of repetitions, and subjects reported their rate of perceived exertion (less than 5 seconds) while sitting to undergo direct cardiovascular measurements (systolic and diastolic blood pressure and heart rate, 30–40 seconds). Ocular measurements (intraocular pressure and central corneal thickness) were uniformly started 60 seconds after the completion of each set. The physiological measurements were conducted in an adjacent space separated from the Smith machine by a partition screen to blind the researcher in charge. At least a five-minute rest was given between sets, and water intake was avoided to prevent intraocular pressure changes due to hydration (Y. W. Kim & Park, 2019). Constant feedback was used in both sessions to ensure proper execution and to encourage maximum effort (McNair et al., 1996).

Squat exercise

A high-bar back squat to a parallel depth (Gene-Morales, Flandez, et al., 2020) was performed using a Smith machine (Multipower Smith machine Powerline PSM144X, Body-

Solid, Salt Lake City, UT, USA). A neutral stance width was established between the hips and shoulders. Shoes were used, but no weightlifting belts or knee wraps were permitted. The tempo consisted of an inhalation-coordinated eccentric phase lasting two seconds (Schoenfeld, 2010b) with a pause of one second at the deepest point and an exhalation coordinated maximum-speed concentric phase (4 seconds for a complete squat). The Valsalva maneuver was avoided due to its influence on intraocular pressure (Y. W. Kim & Park, 2019; McMonnies, 2016; Wylęgała, 2016; Zhu et al., 2018) by asking participants to perform audible breathing. A metronome (Metronome Beats v.4.4.0, Stonekick, London, United Kingdom) set at 60 beats per minute was used to standardize the movement tempo. The depth was adjusted with a horizontal elastic band. The participant had to touch the band (midthigh) in every repetition.

Ocular measurements

Intraocular pressure and central corneal thickness were measured in mmHg and microns, respectively, with a validated noncontact tonometer (Kato et al., 2018; Radhakrishnan et al., 2018). The Auto Kerato-Refracto-Tonometer TRK-1P (Topcon, Tokyo, Japan) automatically compensates for the corneal thickness. The intraclass correlation coefficient of the measurements was 0.91 (coefficient of variation = 6.24%) for the intraocular pressure and 0.93 (coefficient of variation = 0.95%) for the central corneal thickness. Measurements were taken in both eyes in the pilot study. Right eye measurements were used since no significant difference between the eyes was observed.

Mean ocular perfusion pressure was calculated in mmHg using the formula mean ocular perfusion pressure = 2/3 x (mean brachial arterial blood pressure) – intraocular pressure (Cantor et al., 2018; Zhu et al., 2018). The intraclass correlation coefficient of the mean ocular perfusion pressure was 0.89 (coefficient of variation = 6.68%).

Cardiovascular measurements

Cardiac measurements (systolic and diastolic blood pressure and heart rate) were performed using a digital automatic blood pressure monitor (M6W HEM-7213-E [V], Omron Healthcare, Kyoto, Japan) with an intraclass correlation coefficient of 0.90 and a coefficient of variation of 5.49% for the systolic blood pressure, 0.86 and 3.77% for the diastolic blood pressure, and 0.91 and 6.05% for the heart rate. Pulse pressure (mmHg) was calculated as systolic blood pressure – diastolic blood pressure and mean brachial arterial blood pressure (mmHg) as diastolic blood pressure + 1/3 x pulse pressure (Cantor et al., 2018).

Perceived effort measurements

The rate of perceived exertion was measured with the OMNI-RES (Robertson et al., 2003) and OMNI-RES for elastic bands (Colado et al., 2012). Previous studies can be consulted for further details on how to apply these scales (Colado et al., 2014; Colado, Furtado, et al., 2020; Naclerio & Larumbe-Zabala, 2017).

5.1.3 Ethics

The study was conducted in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Permission was provided by the University of Valencia's Ethics Committee on Human Research (H1499867368458). Data reported in the present study form part of a research project investigating different ways of applying elastic resistance in squat performance. All participants voluntarily agreed to participate and were free to withdraw from the study at any time. They signed an informed consent form including a guarantee of data confidentiality.

5.1.4 Statistical analyses

Statistical analyses were performed using the commercial software IBM SPSS Statistics for Macintosh (Version 26.0, IBM Corp., Armonk, NY, USA). The normality of data distribution was assessed using the Shapiro-Wilk test. All physiological variables showed a normal Gaussian distribution ($p > 0.05$). The rate of perceived exertion followed a non-normal distribution ($p \leq 0.05$).

To assess differences and evaluate the influence of the material and the type of effort on the dependent variables, two approaches were employed: 1) a two-way ANOVA with the material (elastic bands and weight plates) and the level of effort (maximal and submaximal) as the within-subject factors and 2) an ANOVA of repeated one-way measurements to evaluate differences between the resting values and the exercise sets. All the cases complied with Mauchly's sphericity assumption. The effect size was evaluated with partial eta squared (ηp^2), where $0.01 < \eta p^2 < 0.06$ constitutes a small effect, $0.06 \leq \eta p^2 \leq 0.14$ a medium-sized effect, and $\eta p^2 > 0.14$ a large effect. Pairwise post-hoc comparisons were completed using the least significant difference correction (LSD). The effect size was calculated as Cohen's *d* with Hedges corrections (Lakens, 2013). This value is reported as unbiased Cohen's *d* (d_{unb};

Cumming, 2014), with $d_{unb} < 0.50$ constituting a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect (Cohen, 1988).

The test-retest relative reliability of the instruments was assessed in a subsample of 10 subjects (two measurements per subject) calculating the intraclass correlation coefficient (Yen & Lo, 2002). The intraclass correlation coefficient was interpreted as poor (< 0.40), moderate (0.40–0.59), good (0.60–0.79), or excellent (≥ 0.80) according to Fleiss (1986). The absolute reliability was verified with the coefficient of variation using the formula (standard error of measurement [SEM] / mean of both measurements) x 100; standard error of measurement is the standard deviation of the difference between the two measurements divided by the square root of the number of measurements per subject (Hopkins, 2000).

Results are reported as mean ± standard deviation [95% confidence interval] and as the median and interquartile range for the nonnormal variables. The significance level was established at $p \leq 0.05$.

5.2 Results

5.2.1 External load

The 75% 1RM used by the subjects for the squat protocol was 95.33 ± 18.08 kilograms with a 95% confidence interval of [87.38–102.97]. As previously mentioned, the number of repetitions for the submaximal sets was established at 9 and 10 with weight plates and elastic bands, respectively. The number of repetitions for the maximal sets was 10.15 ± 0.81 repetitions with a 95% confidence interval of [9.85–10.55] for the set with weight plates and 18.40 ± 4.86 repetitions with a 95% confidence interval of [16.13–20.67] for the set with elastic bands.

5.2.2 Ocular variables

The results of the ocular variables are displayed in Table 9. Significant variations were detected in the intraocular pressure ($F[4, 76] = 19.98$, $p < 0.001$, $\eta p^2 = 0.51$) and mean ocular perfusion pressure ($F[4, 76] = 15.13$, $p < 0.001$, $\eta p^2 = 0.44$) but not in the central corneal thickness ($F[4, 76] = 0.37$, $p = 0.828$, $\eta p^2 = 0.02$) when including the preexercise value in the analysis. Pairwise post-hoc comparisons showed that intraocular pressure and mean ocular perfusion pressure significantly decreased and increased, respectively, compared with baseline levels. The effect of the material ($F[1, 19] = 1.78$, $p = 0.190$, $\eta p^2 = 0.09$), the level of effort ($F[1, 19] = 1.15$, $p = 0.290$, $\eta p^2 = 0.06$), and their interaction ($F[1, 19] = 1.20$, $p = 0.280$, $\eta p^2 =$

0.06) in the intraocular pressure were nonsignificant. Similar results were obtained for the mean ocular perfusion pressure (material: $F[1, 19] = 0.85$, $p = 0.370$, $\eta p^2 = 0.04$; level of effort: $F[1, 19] = 0.04$, $p = 0.840$, $\eta p^2 < 0.01$; interaction material * level of effort: $F[1, 19] = 0.07$, $p = 0.790$, $\eta p^2 < 0.01$).

Table 9. Ocular outcomes for each of the four squat sets.

Condition	IOP (mmHg)	MOPP (mmHg)	CCT (microns)
Baseline	15.05 ± 3.22* [13.54–16.56]	43.45 ± 5.80* [40.74 –46.17]	562.40 ± 29.19 [548.74–576.06]
Set 1 (Max75%1RMWP)	12.85 ± 2.82[(3)] [11.53–14.17]	53.05 ± 8.49 [49.08–57.03]	561.15 ± 30.35 [546.95–575.35]
Δ%	14.62	22.09	0.22
Cohen's d_{unb}	0.73	1.27	0.04
Set 2 (Submax75%1RMWP)	12.80 ± 2.82 [11.48–14.12]	52.59 ± 8.44 [48.64–56.54]	562.65 ± 29.50 [548.84–576.46]
Δ%	14.95	21.03	0.04
Cohen's d_{unb}	0.74	1.21	< 0.01
Set 3 (Max75%1RMEB)	12.30 ± 2.18[(1)] [11.28–13.32]	51.98 ± 8.34 [48.07–55.88]	561.80 ± 28.59 [548.42–575.18]
Δ%	17.95	19.62	0.11
Cohen's d_{unb}	1.00	1.14	0.02
Set 4 (Submax75%1RMEB)	12.75 ± 2.55 [11.56–13.94]	52.10 ± 6.36 [49.12–55.07]	562.00 ± 28.84 [548.50–575.50]
Δ%	15.28	19.89	0.07
Cohen's d_{unb}	0.79	1.36	0.01

Values are presented as mean ± standard deviation [95% confidence interval]. Percentage of variation (Δ%) and effect size (Cohen's *d* unbiased; $d_{unb} < 0.50$ small, $0.50 \leq d_{unb} \leq 0.79$ moderate, and $d_{unb} \geq 0.80$ large) compared with baseline values are displayed. *: statistically significant difference compared to the rest of the conditions. [1, 2, 3, 4]: significant difference ($p < 0.05$) or a trend ($p > 0.05$ to $p < 0.13$ if the number is in brackets), with the condition 1, 2, 3, or 4, respectively. Max: maximum number of repetitions. Submax: submaximal repetitions. %1RMWP: percentage of one repetition maximum with weight plates. %1RMEB: percentage of one repetition maximum with elastic bands. IOP: intraocular pressure. MOPP: mean ocular perfusion pressure. CCT: central corneal thickness.

5.2.3 Cardiovascular variables and perceived effort

Significant differences were observed in all the cardiovascular variables (pulse pressure: $F[4, 76] = 7.94$, $p < 0.001$, $\eta p^2 = 0.30$; mean brachial arterial blood pressure: $F[4, 76] = 8.88$, $p < 0.001$, $\eta p^2 = 0.32$; heart rate: $F[4, 76] = 59.44$, $p < 0.001$, $\eta p^2 = 0.76$). Regarding the heart rate, an influence of the level of effort ($F[1, 19] = 8.12$, $p = 0.010$, $\eta p^2 = 0.30$) and the interaction material * level of effort ($F[1, 19] = 5.44$, $p = 0.030$, $\eta p^2 = 0.22$) was observed, while the influence of the material was nonsignificant. Influences of the material ($F[1, 19] = 7.95$, $p = 0.010$, $\eta p^2 = 0.30$), level of effort ($F[1, 19] = 167.83$, $p < 0.001$, $\eta p^2 = 0.90$), and interaction material * level of effort ($F[1, 19] = 15.55$, $p < 0.001$, $\eta p^2 = 0.45$) on the rate of perceived exertion were observed.

Post-hoc testing revealed that while all the variables significantly increased compared with baseline values, differences among sets only appeared in heart rate and rate of perceived exertion as Table 10 shows.

Table 10. Cardiovascular and perceived effort values for each of the four squat sets.

Condition	PP (mmHg)	MBP (mmHg)	HR (bpm)	RPE
Baseline	58.58 ± 8.04* [55.16–62.16]	87.75 ± 6.97* [84.49–91.01]	63.95 ± 11.27* [59.05–69.21]	-
Set 1 (Max75%1RMWP)	73.42 ± 17.40 [66.26–81.42]	98.85 ± 11.18 [93.62–104.08]	105.26 ± 16.76[(3), 4] [97.95–112.89]	8.55 ± 0.88[2, 4] [8.14–8.96]
Δ%	26.37	12.65	65.05	Median 8.5
Cohen's d_{unb}	1.05	1.14	2.77	IQR: 1
Set 2 (Submax75%1RMWP)	72.25 ± 18.39 [63.00–78.47]	98.08 ± 11.66 [92.63–103.54]	104.47 ± 17.84[3] [97.00–112.16]	7.55 ± 0.99* [7.09–8.01]
Δ%	23.73	11.78	63.09	Median: 7
Cohen's d_{unb}	0.80	1.03	2.61	IQR:1
Set 3 (Max75%1RMEB)	72.20 ± 12.65 [65.74–76.89]	96.42 ± 11.97 [90.82–102.02]	110.89 ± 23.80[(1), 2, 4] [100.53–121.05]	8.65 ± 0.93[2, 4] [8.21–9.09]
Δ%	23.64	9.88	74.28	Median: 9
Cohen's d_{unb}	1.15	0.85	2.42	IQR:1
Set 4 (Submax75%1RMEB)	73.21 ± 12.68 [68.21–79.58]	97.27 ± 8.68 [93.20–101.33]	100.47 ± 16.88[1, 3] [93.42–108.26]	6.50 ± 1.24* [5.92–7.08]
Δ%	25.61	10.85	57.10	Median 6
Cohen's d_{unb}	1.32	1.16	2.44	IQR: 1

Values are presented as mean ± standard deviation [95% confidence interval]. Additionally, median and interquartile range (IQR) are displayed for the rate of perceived exertion (RPE) since it is a nonnormal variable. Percentage of variation (Δ%) and effect size (Cohen's *d* unbiased; $d_{unb} < 0.50$ small, $0.50 \leq d_{unb} \leq 0.79$ moderate, and $d_{unb} \geq 0.80$ large) compared with baseline values are displayed. *: statistically significant difference compared to the rest of the conditions. [1, 2, 3, 4]: significant difference ($p < 0.05$) or a trend ($p \geq 0.05$ to $p < 0.13$ if the number is in brackets), with the condition 1, 2, 3, or 4. Max: maximum number of repetitions. Submax: submaximal repetitions. %1RMWP: percentage of one-repetition maximum with weight plates. %1RMEB: percentage of one-repetition maximum with elastic bands. PP: pulse pressure. MBP: mean brachial arterial blood pressure. HR: heart rate.

5.3 Discussion

Based on the ocular and systemic responses to a squat exercise protocol, this third article of the compendium composing the present doctoral thesis examined whether elastic bands may modulate these acute physiological adaptations to resistance training. Overall, the outcomes of this research were that 1) intraocular pressure significantly decreased and 2) mean ocular perfusion pressure and the cardiovascular values (pulse pressure, mean brachial arterial blood pressure, heart rate) significantly increased after all the exercise sets compared with preexercise values. Although the study hypothesis could not be confirmed and no effect of the material was observed in the ocular variables, the largest drop in intraocular pressure (2.70 mmHg) was observed after a maximal effort with elastic bands at 75% 1RM (see Table 9). Empirical evidence was found indicating that elastic bands facilitate a higher number of repetitions while maintaining similar pulse pressure and mean brachial arterial blood pressure (see Table 10), which have been related to cardiovascular (Glasser et al., 2014) and ocular health (Cantor et al., 2018). Furthermore, the rate of perceived effort and heart rate were not different between performing a mean of approximately 10 repetitions with weight plates and a mean of approximately 18 repetitions with elastic bands both at 75% 1RM.

Considering what has been mentioned in the previous paragraph, it is worth discussing the outputs of this research in light of other empirical experiences that addressed the influence of the external load and other physiological parameters on the intraocular pressure. However, this evidence does not contemplate variable resistance as a method of loading the bar.

Squatting with elastic bands reduces the weight at the bottom phases of the squat, during which a mechanical disadvantage occurs (V. Andersen et al., 2015; Saeterbakken et al., 2016). Beyond this point, elastic bands add progressively more resistance/weight until the end of the movement. Thus, exercising with elastic bands can increase the weight in the region of the range of motion that is more mechanically effective accompanied by reduced weight in the less efficient range (V. Andersen et al., 2015; Gene-Morales, Gené-Sampedro, et al., 2020; Saeterbakken et al., 2016). This feature of the elastic bands allowed subjects to perform more repetitions, which is useful to promote muscle adaptations (Burd et al., 2012; Tamura et al., 2013; Walker et al., 2011). The combination of all these facts argues in favor of the incorporation of elastic bands in resistance training programs. Additionally, the use of elastic bands in this study provoked similar values of postexercise intraocular pressure as the use of weight plates did (maximal effort: mean difference 0.55 mmHg, 95% confidence interval [-0.12–1.22], p = 0.100, d_{unb} = 0.21; submaximal effort: mean difference 0.05 mmHg, 95% confidence interval [-0.62–0.72], p = 0.870, d_{unb} = 0.02). This combination of findings suggests that elastic bands are an appropriate device to load the bar for squat exercises when looking for high volumes and conservative ocular responses. To support these findings, independent variables included in our study and their influence on intraocular pressure are discussed below.

The independent variable of the external load addressed by the expert literature as having major relevance for the changes in ocular physiology is the weight. Most of the current literature reports higher intraocular pressure values with greater weights (Avunduk et al., 1999; Conte & Scarpi, 2014; Rüfer et al., 2014; Tamura et al., 2013; Vera, García-Ramos, et al., 2017; Vera, Jiménez, Redondo, Cárdenas, et al., 2018; Vera, Jiménez, Redondo, Torrejón, De Moraes, et al., 2019). In contrast with the weight, performing more repetitions has been related to lower intraocular pressure values (Conte & Scarpi, 2014; Rüfer et al., 2014; Tamura et al., 2013; Vera, Jiménez, Redondo, Torrejón, et al., 2018). In our study, the set with a larger number of repetitions (maximum effort at 75% 1RM with elastic bands) provoked the lowest intraocular pressure (12.30 mmHg), although the differences from the rest of the sets were not significant. Supporting the influence of the number of repetitions on intraocular pressure, differences were not found between performing 9 and 10.15 repetitions with weight plates or between 9 and 10 repetitions with weight plates and elastic bands, respectively. Lower intraocular pressure values in response to a larger number of repetitions may be due to acute physiological adaptations to higher volumes of exercise such as modifications in plasma pressures, biochemical responses (McMonnies, 2016; Walker et al., 2011; Wylęgała, 2016; Zhu et al., 2018), and higher levels of blood lactate (Tamura et al., 2013; Teixeira et al., 2019). Understanding that less weight allow for more repetitions (and higher intensities for lower volumes; Shimano et al., 2006), it is important to address the possible influence of the level of effort within the ocular acute adaptations to resistance training.

The level of effort (i.e., the number of repetitions performed out of the maximum possible) has been shown to influence intraocular pressure and mean ocular perfusion pressure behavior, with certain controversy regarding the safety of performing maximal efforts (Conte et al., 2009; Tamura et al., 2013; Vera, Jiménez, Redondo, Torrejón, et al., 2018). While one study reported reductions in intraocular pressure after a maximum number of repetitions at 60% 1RM (Tamura et al., 2013), other authors recommended not including maximal efforts when aiming at avoiding intraocular pressure increases and mean ocular perfusion pressure decreases (Vera, Jiménez, Redondo, Torrejón, et al., 2018). Our results indicate that no difference existed between performing a maximal or submaximal effort at 75% 1RM with weight plates (mean difference 0.05 mmHg, 95% confidence interval [-0.59–0.69], $p = 0.870$, $d_{unb} = 0.02$) or elastic bands (mean difference 0.45 mmHg, 95% confidence interval [-0.15−1.05], $p = 0.130$, $d_{unb} = 0.18$).

All cardiovascular parameters were significantly modified from preexercise values. However, differences between sets only emerged in the rate of perceived exertion and heart rate. No influence of the elastic bands compared to weight plates was observed for the blood pressure values (mean brachial arterial blood pressure and pulse pressure), as happened with the mean ocular perfusion pressure. Bearing in mind these results and while caution should be applied, resistance training with elastic bands could be performed by people with hypertension risk just as it can be performed with weight plates (Sorace et al., 2009, 2012). It must be noted that the set that caused the highest heart rate (maximal effort at 75% 1RM with elastic bands), coinciding with the greatest number of repetitions, was also the set with the lowest intraocular pressure values, although, and as previously mentioned, the differences were not significant. This fact is probably related to the total volume of work, which increases heart rate (Gjovaag et al., 2016) and modulates intraocular pressure responses (McMonnies, 2016; Wylęgała, 2016; Zhu et al., 2018). As could be expected, the maximal sets were perceived as more demanding than the submaximal sets. It is also worth highlighting that a maximal effort at 75% 1RM with elastic bands was not perceived as more demanding than a maximal effort at 75% 1RM with weight plates, while the set with elastic bands included a greater number of repetitions.

All the aforementioned variations may be due to different physiological, homeostatic mechanisms. First, intraocular pressure variations were not mediated by central corneal thickness changes since this variable remained stable within all the conditions. This confirms the findings of Read and Collins (2011) on stable central corneal thickness values after moderate-intensity bicycle ergometer exercise and supports the hypothesis of Wylęgała et al. (2016) that the increases reported in central corneal thickness after high-altitude climbing might be attributed to low oxygen concentration at higher altitudes rather than to the exercise effect. As for the mean ocular perfusion pressure, exercise-induced changes seem to be mediated by the blood pressure rather than by the intraocular pressure, which confirms previous research on the relationship between ocular perfusion pressure and blood pressure (Cantor et al., 2018; Costa et al., 2014; McMonnies, 2016; Wylęgała, 2016; Zhu et al., 2018).

5.3.5 Limitations

Although all the procedures and analyses were carefully designed and conducted, some limitations should be listed. First, validated air-puff tonometry was chosen because it is easy to use and does not require the use of anesthesia (Kato et al., 2018; Radhakrishnan et al., 2018). However, future studies should standardize a method of continuous intraocular pressure measurement (Y. W. Kim et al., 2015), and thus, this study should be replicated by continuously monitoring the intraocular pressure responses during squats and for a prolonged period after the exercise to create a daily curve. Diagnosed or suspected glaucoma patients and elderly subjects should be included with a greater sample size. Furthermore, even though the order of the sets was randomized (across subject counterbalance), future studies should test all the sets in a complete counterbalanced order to be able to determine the effects of the order of exercises on the ocular responses. Blood pressure and mean ocular perfusion pressure were estimated with formulas since direct measurements have been proven difficult to conduct in laboratory practices (Costa et al., 2014). However, heart rate significantly changed between sets, and this may modulate the fraction of systole (which is used in the mean brachial arterial blood pressure formula as the constant; Chemla et al., 2005). Additionally, a method to equalize the weight between elastic bands and weight plates as recently proposed (Gene-Morales, Gené-Sampedro, et al., 2020) would help to better understand ocular responses to both materials.

5.4 Conclusion

This research emphasizes the potential practical applications of using elastic bands to maintain safe postexercise levels in the analyzed ocular and cardiovascular health-related parameters. More specifically, data from this study indicate that postexercise intraocular pressure is lower and mean ocular perfusion pressure, pulse pressure, and mean arterial blood pressure higher compared with preexercise values after maximal and submaximal efforts and with both elastic bands and weight plates. These results only partially confirm the third hypothesis of the present doctoral thesis. This combination of findings provides some support for the usefulness of elastic bands to perform resistance training and, while further research in this regard is needed, suggests that ocular and cardiovascular health can be preserved with their use.

Chapter 6. Future research

6. Future research

The procedures completed within the present doctoral research establish the foundation for a new application of elastic bands for resistance training and suggest that their use could be appropriate to maintain comparable ocular and cardiovascular responses to traditional resistance training devices (i.e., weight plates). In this line, future research is guaranteed to further evaluate the potential health and performance benefits of using elastic bands to load the bar for resistance training.

The following sections develop future research lines directly associated with the results obtained in the present doctoral thesis. This chapter is divided into two sections along performance and health research lines.

6.1 Future research focused on performance

Chapter 4 shows interesting results regarding performance. Although we used a Smith machine looking forward to ensuring equal conditions among all the subjects, the study should be replicated using a free barbell. Furthermore, this new procedure of using the height at the sticking point to add the pertinent weight using elastic bands could be used in different resistance training exercises that have a measured sticking point such as the deadlift and the bench press.

In the studies included in the present doctoral thesis, we did not measure the weight at the deepest position of the squat. Consequently, the most relevant point that future research should address is a method to equate the average weight provided by elastic bands throughout the range of motion and the weight provided by weight plates (e.g., measuring the weight at different points of the range of motion with elastic bands and comparing the average with weight plates). In similar studies completed by our research group, we found a decrease of approximately 15% in the load from the sticking point to the lowest point of the range of motion (in our pilot studies, located at 81.12 ± 3.74 knee joint angle degrees). Considering the results of Chapter 4, it seems that when the pertinent weight is applied immediately above the sticking point, participants use the same weight as with weight plates at this point, 15% fewer weight at the deepest position, and 25% more weight at the standing position. This distribution of the weight throughout the range of motion could be optimal for strength application, and therefore future research should compare activation levels and velocity of the barbell throughout the range of motion.

Second, even though we did not analyze this condition, our results suggest that 25% more of the pertinent load could be directly added to the bar at the standing position using elastic bands, with no need to measure the sticking point. Additionally, while caution should be applied until more scientific evidence arrives, the strategies presented may allow the trainer or the athlete to select, according to their necessities, the optimal point of loading the elastic resistance to maximize their physical performance and/or perceptual responses.

Finally, all the procedures in this study were focused on identifying acute variations in the training load, and therefore it would be interesting to introduce the use of the loading immediately above the sticking point with elastic bands in a short- or long-term resistance periodization program to check for chronic adaptations in central neural activation, muscle hypertrophy, and strength development.

6.2 Future research focused on health

The results of the present doctoral thesis regarding ocular health have been the foundation for future works associated with intraocular pressure and exercise. More specifically, a study comparing the effect of different levels of leg blood flow restriction during squats on the variations of intraocular pressure is currently under review (see Appendix 9.2.2). In that study, we measured intraocular pressure after each repetition, obtaining increments during exercise and drops after exercise. Participants had to stop for only a few seconds in the standing position to undergo intraocular pressure measurements, but this could affect the exercise performance. Future studies using continuous intraocular pressure monitoring with these methodologies could provide robust information on the actual behavior of intraocular pressure during each exercise phase (e.g., concentric, eccentric).

Considering the controversial results found in the literature regarding intraocular pressure variations with resistance training (see Section 1.2.1), a systematic review with meta-analysis is being conducted to assess whether the point of measurement (i.e., during or after exercise) or other methodologies (e.g., use of the Valsalva maneuver, the position of measurement, and the device employed for the measurement) significantly affect intraocular pressure outcomes. Although that article is not finished, it seems that intraocular pressure increases during exercise and decreases immediately after, with significant drops after approximately one minute. Added to this, one study found decreases in resting intraocular pressure after a four-week resistance training program in primary open-angle glaucoma patients (Ibrahim & Elbeltagi, 2019). Bearing these facts in mind, the question arises whether intraocular pressure could follow similar patterns as blood pressure, which increases during exercise but chronically decreases in the long term due to different adaptations. More clinical trial intervention studies are needed to test this hypothesis and potentially provide the dose-response of exercise in reducing intraocular pressure in the long term.

Finally, attending to the prediction potential of baseline intraocular pressure for intraocular pressure variations due to the exercise (Gene-Morales et al., 2021), a third study to evaluate the influence of corneal biomechanical parameters in the intraocular pressure variations after exercise in athletes was conducted. Data are yet to be analyzed.

Chapter 7. Conclusions

7. Conclusions

The present doctoral thesis includes two articles related to the use of elastic bands to load the bar in squats and its potential benefits for performance and the maintenance of ocular and cardiovascular health (see Appendices 9.1.3 and 9.1.4). Additionally, two preliminary articles were conducted to analyze the prediction potential of sociodemographic and ocular parameters on the intraocular pressure variations after combined exercise (Appendix 9.1.1) and to select the most appropriate squat variation for the present project (Appendix 9.1.2), respectively. In addition, three more scientific articles (Appendix 9.2.1) and 15 congress communications (Appendix 9.2.3) directly related to the subject of the present thesis have been published. One article analyzing the effects of squatting with leg blood flow restriction on intraocular pressure variations is currently under review (Appendix 9.2.2), and four more articles are being written. All the scientific contributions of the doctoral candidate, whether derived from this doctoral project or not, can be found in Appendix 9.

The main conclusions of each of the four articles are presented hereafter divided into four sections according to the aims of each study.

7.1 The prediction potential of sociodemographic and ocular parameters for intraocular pressure variations

The results presented in the first article of this compendium (see Chapter 2; Gene-Morales et al., 2021) illuminate the behavior of specific ocular parameters after exercise. This article reveals that intraocular pressure behavior after exercise is multifactorial, with several individual factors influencing the intraocular pressure responses after exercise. Therefore, future research or professionals working with people with glaucoma risk factors should account for sociodemographic and physiological differences when assessing intraocular pressure variations with exercise.

7.2 Selection of the squat variation

The study included in Chapter 3 (Gene-Morales, Flandez, et al., 2020) highlights the importance of studying the neuromuscular acute effects of the squat to deeply understand the exercise and its variations in order to individualize resistance training programs. The high-bar back squat is the most commonly studied squat variation in the scientific literature with relatively homogeneous results. Additionally, using a Smith machine to squat reduces instability and nonvertical displacement of the bar. Therefore, a guided high-bar back squat with neutral joint positioning seemed the best option to test new squat methodologies such as that presented in Chapter 4.

7.3 The usefulness of elastic bands to maximize the weight used in squats and optimize performance and perceived effort

The combination of findings of the article included in Chapter 4 (Gene-Morales, Gené-Sampedro, et al., 2020) comprises a novel approach to the use of elastic bands for resistance training. Elastic bands can be used to load the bar with the pertinent weight added immediately above the knee sticking point in squats to maximize the number of repetitions performed and weight used while maintaining similar internal load responses. Athletes and strength and conditioning professionals could benefit from this new application of elastic bands.

7.4 The usefulness of elastic bands to provoke conservative ocular and cardiovascular responses

The fourth article of the present compendium presented in Chapter 5 (Gene-Morales et al., 2022) contributes to the multidisciplinary collaboration between optometrists, ophthalmologists, and strength and conditioning professionals in the management and prevention of glaucoma. Professionals working with people with glaucoma risk factors should instruct their clients or patients to control the technique and movement tempo and avoid the Valsalva maneuver. Bearing this in mind, both elastic bands and weight plates could be interchangeably used depending on the aims of the training program without obtaining significant differences in the ocular and cardiovascular variables analyzed.

The present doctoral thesis highlights the multidisciplinary collaboration between strength and conditioning professionals, optometrists, and ophthalmologists in the prevention, management, and treatment of increased intraocular pressure and other risk factors associated with primary open-angle glaucoma.

Chapter 8. References

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[1] Several in-text citations of the present doctoral thesis include the initial of the first author according to Section 8.20 of the Publication Manual of the American Psychological Association (American Psychological Association, 2020, pp. 408–409):

> "If the first authors of multiple references share the same surname but have different initials, include the first authors' initials in all in-text citations, even if the year of publication differs. Initials help avoid confusion within the text and help readers locate the correct entry in the reference list (see Section 9.48)."

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Chapter 9. Appendices

9. Appendices

9.1 Information of the articles included in the compendium

1. **Gene-Morales, J.**, Gené-Sampedro, A., Martín-Portugués, A., & Bueno-Gimeno, I. (2021). Do age and sex play a role in the intraocular pressure changes after acrobatic gymnastics? *Journal of Clinical Medicine, 10*(20), 4700.
2. **Gene-Morales, J.**, Flandez, J., Juesas, A., Gargallo, P., Miñana, I., & Colado, J. C. (2020). A systematic review on the muscular activation on the lower limbs with five different variations of the squat exercise. *Journal of Human Sport and Exercise*, *15*(Proc4), S1277–S1299.
3. **Gene-Morales, J.**, Gené-Sampedro, A., Salvador, R., & Colado, J. C. (2020). Adding the load just above the sticking point using elastic bands optimizes squat performance, perceived effort rate, and cardiovascular responses. *Journal of Sports Science & Medicine*, *19*(4), 735–744.
4. **Gene-Morales, J.**, Gené-Sampedro, A., Salvador, R., & Colado, J. C. (2022). Effects of squatting with elastic bands or conventional resistance-training equipment at different effort levels in the post-exercise intraocular pressure of healthy men. *Biology of Sport*, *39*(4), 895–903.

Article	Citations#	Journal	Impact factor*	Citation indicator	Area	Rank	Quartile
1	1	Journal of Clinical Medicine	4.242	1.24	Medicine, General & Internal	39/167	Q1
2	1	Journal of Human Sport and Exercise	Emerging Sources Citation Index (ESCI)	0.44	Sport Sciences	80/116	Q3
3	4	Journal of Sports Science and Medicine	2.988	0.89	Sport Sciences	36/88	Q2
4	1	Biology of Sport	2.806	0.93	Sport Sciences	44/88	Q2

Source: https://scholar.google.com/citations?user=3gCdPoAAAAAJ&hl=es; * Source: Journal Citation Reports, year 2020.

9.1.1 Article 1

Journal of
Clinical Medicine

MDPI

Article

Do Age and Sex Play a Role in the Intraocular Pressure Changes after Acrobatic Gymnastics?

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Abstract: To evaluate the effects of an acrobatic gymnastics (AG) training session on intraocular pressure (IOP), a familiarization session was employed to confirm the participant's suitability for the study. Forty-nine gymnasts (63.27% females, 18–40 years old) voluntarily agreed to participate. As age, sex, baseline IOP, and central corneal thickness (CCT) were considered as potential predictors of the IOP variations, in the second session measurements of the above parameters were taken before and after 90 min of AG. A mixed-factorial analysis of variance evaluated differences. Linear regression was conducted to potentially predict the IOP variation with the exercise. After the scheduled exercise, highly significant ($p < 0.001$, effect size: 0.73) reductions in IOP, but no significant changes in CCT ($p = 0.229$), were observed. IOP was significantly modified in males, older than 25 years, and subjects with baseline IOP > 14 mmHg ($p \leq 0.001$, effect sizes: 0.57–1.02). In contrast, the IOP of females, younger participants, and subjects with baseline IOP $\leq$ 14 mmHg was not significantly modified ($p = 0.114$). With the regression analyses, we concluded that both sex and baseline IOP levels were significant predictors of the IOP fluctuation with AG. These findings could be of interest for gymnasts, coaches, ophthalmologists, and/or optometrists in the prevention and control of risk factors associated with glaucoma.

Keywords: physical exercise; sport; acrobatic gymnastics; baseline intraocular pressure; central corneal thickness; ocular health; tumbling skills; hand balance

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1. Introduction

Intraocular pressure (IOP) and its fluctuations are still recognized as the main modifiable factor in the control, management, and prevention of glaucoma [1–3]. IOP can fluctuate due to different internal and external factors. Among them, age and sex are acknowledged factors that condition IOP [4,5]. Additionally, corneal thickness [6] and baseline IOP levels [2,7] have been identified to play a role in the short-term IOP fluctuations. As far as we know, no previous research has analyzed the potential effects of baseline IOP levels and corneal thickness (CCT) on the IOP fluctuations caused by acrobatic gymnastics (AG) exercise.

Exercise is a key external factor that modifies intraocular pressure [3–5,8,9] and cardiovascular parameters [10]. More specifically, aerobic, continuous exercise such as running or cycling at low to moderate intensities has proven to acutely reduce IOP [8,11–13]. Regarding resistance exercises involving muscular strength such as weightlifting, controversial results appear in the scientific literature, with many studies ensuring IOP elevations [14–20] and other studies reporting IOP reductions due to the exercise effect [21–30]. As shown in previous expert literature, recovery of pre-exercise IOP values could take from several minutes after resistance exercises to up to one hour after aerobic exercise [4,8]. In addition to the exercise methodology itself, certain positions during the activity such as head-down positions could increase IOP [3,5,8]. Considering the above concerns, it remains necessary to study sport disciplines that in their practice combine the aerobic and muscular systems and changes of position, such as AG. Nevertheless, knowledge on AG remains incomplete [31], especially in terms of ocular adaptations. No previous studies dealing with IOP variations after AG were found.

AG is growing in popularity among different age groups [31,32]. AG is a combined activity that can be performed in pairs or groups and includes static elements such as balances and figure holds (hand balances, bridges, splits, human pyramids) and dynamic elements such as partner lifts, throws with complex somersaults and twists, and tumbling skills [33–35]. This motor and social sport requires high levels of strength, flexibility, balance, agility, coordination, speed, and cardiovascular performance [36]. Due to the aforementioned topics, it is scientifically necessary to evaluate the IOP acute adaptations that could occur after an AG session, to obtain a better understanding of the effects of this activity that could not be reached within a laboratory environment. Furthermore, the question arises as to whether sociodemographic and ocular variables such as sex, age, baseline IOP, and baseline CCT could play a role in the IOP variations.

The main aim was to evaluate IOP and CCT variations after an AG session. Additionally, a set of demographics (age and sex) and ocular parameters (baseline IOP and CCT) were considered as potential predictors of the IOP variation due to the exercise effect (difference between post-exercise and pre-exercise intraocular pressure values).

We hypothesized that exercise would reduce the IOP and CCT would remain unchanged. We also expected to find that the independent variables (age, sex, baseline IOP, and CCT) would affect the IOP variations.

2. Materials and Methods

An observational, prospective, longitudinal study was conducted to compare the IOP and CCT of gymnasts pre- and post-exercise. Additionally, the prediction potential of age, sex, baseline IOP, and CCT on the variation of IOP was addressed. We conducted the study in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki [37]), and ethical approval was provided by the Research Ethics Committee on human research of the University of Valencia (H1499867368458). The study was also approved by the Club Dynamic Gym of Manises (Valencia, Spain). The subjects were informed of the study characteristics and protocols, and signed, informed consent was obtained from all the participants at the beginning of the procedures. Participants were free to withdraw from the study at any time. Data were confidential and participation was anonymous, implying no potential risks for the integrity of the subjects apart from those derived from the physical activity.

2.1. Participants

The sample size was determined by a priori power analyses, assuming an α of 0.05, power levels (1-ß) of between 0.80 and 0.95, a non-sphericity correction of $\varepsilon = 1$, and an effect size of f(V) = 0.45 for ANOVA tests and $f^2 = 0.24$ for the regression analyses. Thus, 49 participants were recruited for this study. Main inclusion criteria were: (1) older than 18 and younger than 40 years old, (2) experience with acrobatic gymnastics of at least 6 months and performing at least 2 days per week, (3) no musculoskeletal issues, (4) baseline IOP between 10.00 and 21.00 mmHg, (5) normal anterior chamber depth, (6) no history of ophthalmic laser procedures, ocular surgery, traumatism, or use of topic/systemic medications potentially affecting the IOP. Subjects with a family history of glaucoma and/or contact lens wearers were excluded from this study.

At the beginning of the study, 51 athletes were recruited, but only 49 met the criteria (18 male and 31 female). All these subjects voluntarily agreed to participate in the study. Participants were classified into two groups according to their age: (1) adults (>25 years old) and (2) young adults (≤25 years old) [38]. Additionally, three more groups were formed regarding the baseline IOP levels (low, medium, and high). For such purpose, baseline IOP was divided into terciles (with limits at 14 and 17 mmHg) as previously reported [2,7]. Further characteristics of the sample, including demographics and spherocylindrical refraction values, are reflected in Table 1. The spherocylindrical refraction values were converted to power vector notation (M, J0, and J45). Refractive error was determined in terms of (1) the spherical equivalent (M component) and (2) a pair of Jackson Crossed Cylinder lenses oriented at 0°/90° (J0 component) and 45°/135° (J45 component) for determination of astigmatism. Refractive error was measured to characterize the sample considering its potential influences on IOP [39].

Table 1. Characteristics of the general sample (n = 49).

Variable	Mean	Standard Deviation	95% Confidence Interval	
			Lower	Upper
Age (years)	27.67	7.10	25.66	29.69
M (D)	−0.86	1.62	−1.32	−0.41
J0 (D)	−0.01	0.31	−0.09	0.08
J45 (D)	−0.03	0.15	−0.07	0.02

M: spherical equivalent; J0 and J45: Jackson crossed cylinder lenses, representing the three components of refractive error in power vector notation; D: diopters.

All participants were instructed to avoid alcohol/tobacco consumption and to not perform vigorous exercise 24 h before any programmed session. They were asked to sleep for at least 8 h, to not consume stimulants, to not drink more than 1 L of liquids [4], and to not perform prolonged near-viewing activities within the 3 h before the trials [40].

2.2. Procedures

All procedures were conducted in the same gymnastic facilities by the same researchers (one optometrist (in charge of the measurements) and one sports scientist (responsible for the gymnastics session)). All data were collected in a thermoneutral environment (~22 °C and ~60% humidity), under the same lighting, and at the same period (between 7:20 p.m. and 9:10 p.m.) to reduce the effects of circadian rhythm variations in the eyes [41]. Measurement tools were installed in a room next to the training facilities to improve access and performance of techniques. Two sessions separated by 1 week were scheduled: one for assessment of sociodemographic data, participants' characteristics, and systematized ophthalmological examination at baseline, and a second session to carry out all experimental procedures to evaluate the dependent variables before and after the AG session.

In the first session, an ocular examination was performed to ensure the validity of participants, including measurements of best-corrected visual acuity, subjective refraction, IOP (Auto Kerato-Refracto-Tonometer TRK-2P; Topcon®, Tokyo, Japan), stereopsis, motility, and biomicroscopic anterior eye segment examination (Slit Lamp SL-D4, Topcon Europe Medical BV, The Netherlands). Objective refraction was measured with the Auto Kerato-Refracto Tonometer (TRK-2P, Topcon®, Tokyo, Japan) and was followed by a subjective refinement.

In the second session, pre-exercise eye parameters were measured 5 to 10 min before starting the exercise. All subjects underwent the same 90-min acrobatic gymnastics training session (as reflected in the previous section, for further information on the specific characteristics of this type of sport). IOP and CCT were measured again 5 to 10 min after finishing the exercise.

Intraocular Pressure and Central Corneal Thickness

As above reflected, IOP and CCT were measured in mmHg and microns, respectively, with the Auto Kerato-Refracto-Tonometer TRK-2P (Topcon®, Tokyo, Japan). This non-contact instrument is composed of Rotary Prism Technology and provides unmatched accuracy and reliability as well as permitting accurate and reliable measurements with a pupil as small as 2 mm in diameter. The device uses optical pachymetry to determine CCT, which involves using a tangential slit of light directed onto the cornea at a known angle. The illuminated slit is measured, and corneal thickness is calculated using trigonometry. All parameters, including horizontal and vertical alignment and vertex distance, were determined by the instrument. Additionally, TRK-2P allows adjusting the value of pneumotonometry with pachymetry, so that it automatically adjusts the IOP value based on corneal thickness [42]. The measurements were taken using the full screening mode, which includes intraocular pressure, keratometry, autorefraction, and pachymetry values. Three readings for each patient were obtained, averaged, and recorded.

Measurements were taken in both eyes in this study. Right eye measurements were used since no significant difference (p = 0.112) was observed between the eyes.

2.3. Statistical Analysis

First, a basic data curation was performed, and descriptive statistics of the sample features were calculated. Variation of IOP was calculated as post-exercise IOP minus pre-exercise IOP, which, in turn, was converted to a percentage (Δ%). Normality of data distribution and homoscedasticity was assessed through the Shapiro–Wilk and Levene tests, respectively. Data showed a normal-Gaussian distribution with homogeneous variances.

At this point, a mixed factorial analysis of variance (ANOVA), with the exercise (baseline and post-exercise measurements) as the within-subject factor, and sex (male, female), age (young adult, adult), and baseline IOP levels (low, medium, high) as the between-subject factors, was used to evaluate the effects of the exercise as well as to assess differences in the study-dependent variables. Effect size was evaluated with eta partial squared (ηp^2), where $0.01 < \eta p^2 < 0.06$ constitutes a small effect, $0.06 \leq \eta p^2 \leq 0.14$ constitutes a medium effect, and $\eta p^2 > 0.14$ constitutes a large effect. Pairwise post hoc comparisons were evaluated using Bonferroni correction. The effect size for post hoc comparisons was calculated as Cohen's d with Hedges' corrections to avoid biases due to sample size or standard deviation differences [43]. This corrected value is reported as unbiased Cohen's d (d_{unb}) [44], with $d_{unb} < 0.50$ constituting a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect [45].

Afterward, Multiple Linear Regression analyses (MLR–method: enter) were carried out for the variation of intraocular pressure (difference between post-exercise and pre-exercise IOP values). Two models' fit were tested as potential predictors of the IOP variation, one including socio-demographic (age and sex) and one including ocular variables (baseline levels of IOP and CCT).

All the statistical analyses were carried out using the software IBM SPSS Statistics for Macintosh (Version 26.0; IBM Corp., Armonk, NY, USA), while statistical power analyses were carried out with the software G*Power (Version 3.1.9.6; [46]). The level of statistical significance was set at $p < 0.05$, and tendencies were identified from $0.05 \leq p \leq 0.13$.

3. Results

The ANOVA performed on IOP revealed a significant effect of the exercise ($F[1, 43] = 33.77$, $p < 0.001$, $\eta p^2 = 0.46$), the interaction exercise*sex ($F[1, 43] = 6.53$, $p = 0.015$, $\eta p^2 = 0.14$), and exercise*age ($F[1, 43] = 7.76$, $p = 0.008$, $\eta p^2 = 0.17$). The interaction exercise*baseline IOP levels resulted non-significant, although with medium effect size ($F[2, 43] = 1.70$, $p = 0.196$, $\eta p^2 = 0.08$). All the rest of the interactions analyzed were not significant ($p > 0.05$). Regarding the CCT, the ANOVA revealed a non-significant effect of exercise ($F[1, 43] = 3.97$, $p = 0.05$, $\eta p^2 = 0.09$), or for any of the interactions analyzed (exercise*sex: $F[1, 43] = 3.62$, $p = 0.064$, $\eta p^2 = 0.09$; exercise*age: $F[1, 43] = 0.70$, $p = 0.407$, $\eta p^2 = 0.02$; exercise*baseline IOP levels ($F[2, 43] = 0.24$, $p = 0.788$, $\eta p^2 = 0.01$). Table 2 presents the general results of the sample. It is worth highlighting that, while IOP was significantly modified ($p < 0.001$), as a consequence of the exercise, with a moderate-large effect size (d_{unb} = 0.73), CCT showed non-significant differences from pre- to post-exercise experimental points (p = 0.229).

Table 2. Data comparison between the pre- and post-exercise intraocular pressure values in the study participants (n = 49).

	Pre-Exercise	Post-Exercise	Δ%	p-Value	Cohen's d_{unb}
IOP (mmHg)	15.28 ± 0.95 [14.78–15.83]	14.30 ± 1.61 [13.93–14.97]	−6.27	<0.001	0.73
CCT (microns)	557.34 ± 35.51 [544.78–566.05]	557.91 ± 35.23 [545.98–566.94]	0.19	0.229	0.03

Post hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). Cohen's d represents the effect size of the pre- and post- differences, being d_{unb} < 0.50 a small effect, 0.50 ≤ d_{unb} ≤ 0.79 a moderate effect, and d_{unb} ≥ 0.80 a large effect.

3.1. Between-Group Comparisons

Bonferroni's post hoc comparisons for the IOP and CCT results are presented in Table 3 (sex), Table 4 (age), and Table 5 (baseline IOP levels grouping). First, regarding between-sexes comparisons, significant differences were found in pre- (p = 0.01, d_{unb} = 0.59) and post-exercise intraocular pressure (p = 0.04, d_{unb} = 0.45), but not in the CCT (pre-exercise, p = 0.097; post-exercise, p = 0.071). Highly significant differences were detected between sexes in the value of the variation of IOP (Δ%), with a significantly higher reduction found in males (mean difference (m.d.) 1.60 mmHg, 95% CI [1.11–2.13], p < 0.001, d_{unb} = 1.50). Concerning the pre- and post- comparison (within-group comparison), on the one hand, male athletes obtained a significant decrease in IOP with a large effect size (d_{unb} = 1.02). On the other hand, the variation of this variable was non-significant in females (p = 0.312). It is also remarkable that CCT was significantly modified (p = 0.007) from pre- to post-exercise in females, with the effect size being negligible (d_{unb} = 0.03).

The post hoc analyses performed for age showed significant between-group differences in the post-exercise IOP values (m.d. 1.17 mmHg, 95% CI [1.12–1.22], p = 0.016, d_{unb} = 0.50), but not in the pre-exercise values (m.d. 0.02 mmHg, 95% CI [0.01–0.05], p > 0.05). Additionally, both age groups showed a statistical tendency of significantly different IOP variation (Δ%) with moderate effect size (m.d. 0.75 mmHg, 95% CI [0.09–0.98], p = 0.07, d_{unb} = 0.50). Only the subjects over 25 years old presented significant (p < 0.001) IOP fluctuations from pre- to post-exercise with a moderate-large effect size (d_{unb} = 0.78). The young adults did not show significant fluctuations with the exercise (p = 0.154). No significant changes were observed for either of the groups in terms of the CCT (young adults: p = 0.605; adults: p = 0.243).

Table 3. Data comparison between the pre- and post-exercise intraocular pressure values, according to the sex of the participants (males, n = 18; females, n = 31).

	Group	Pre-Exercise	Post-Exercise	Δ%	p-Value	Cohen's d_{unb}
IOP (mmHg)	Male	15.60 ± 1.31 * [15.28–16.04]	13.82 ± 2.29 * [13.06–14.38]	−11.41 **	<0.001	1.02
	Female	14.91 ± 1.04 [15.11–15.71]	14.73 ± 1.81 [14.66–15.70]	−1.20	0.312	0.15
CCT (microns)	Male	546.94 ± 57.95 [526.11–559.51]	546.66 ± 57.13 [526.93–559.85]	0.09	0.395	0.01
	Female	568.02 ± 45.73 [554.84–581.20]	569.53 ± 45.09 [556.54–582.52]	0.27	0.007	0.03

Post hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). * and ** characterize statistically significant and highly statistically significant differences between sexes, respectively. Cohen's d represents the effect size of the pre- and post- differences, with d_{unb} < 0.50 being a small effect, 0.50 ≤ d_{unb} ≤ 0.79 a moderate effect, and d_{unb} ≥ 0.80 a large effect.

Table 4. Data comparison between the pre- and post-exercise intraocular pressure values, according to the age of the participants (young adults [minor or equal to 25 years], $n = 21$; adults [older than 25 years], $n = 28$).

	Group	Pre-Exercise	Post-Exercise	Δ%	p-Value	Cohen's d_{unb}
IOP (mmHg)	Young adults	15.27 ± 1.30 [14.89–15.64]	14.88 ± 2.21 * [14.25–15.52]	−2.55	0.154	0.21
	Adults	15.25 ± 1.39 [14.84–15.65]	13.71 ± 2.37 [13.03–14.40]	−10.10	<0.001	0.78
CCT (microns)	Young adults	564.62 ± 58.28 [547.78–581.46]	564.95 ± 57.74 [548.27–581.64]	0.06	0.605	0.00
	Adults	550.05 ± 62.57 [531.97–569.13]	550.87 ± 62.00 [532.95–568.78]	0.15	0.243	0.01

Post hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). * characterize statistically significant differences between age groups. Cohen's d represents the effect size of the pre- and post- differences, with $d_{unb} < 0.50$ being a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect.

Table 5. Data comparison between the pre- and post- exercise intraocular pressure values, according to the baseline IOP of the participants (lowest [≤14.00 mmHg], $n = 18$; medium [14.01 to 16.99 mmHg], $n = 17$; highest [≥17.00 mmHg], $n = 14$).

	Group	Pre-Exercise	Post-Exercise	Δ%	p-Value	Cohen's d_{unb}
IOP (mmHg)	Low	13.42 ± 1.43 ** [13.00–13.83]	12.91 ± 2.50 ** [12.19–13.63]	−3.80 [3]	0.114	0.25
	Medium	15.75 ± 1.44 ** [15.33–16.17]	14.56 ± 2.53 * [13.83–15.29]	−7.56	0.001	0.57
	High	17.44 ± 1.46 [17.02–17.86]	15.88 ± 2.56 [15.14–16.61]	−8.95	<0.001	0.74
CCT (microns)	Low	551.58 ± 63.13 [533.39–569.77]	552.70 ± 62.24 [534.77–570.63]	0.20	0.136	0.02
	Medium	552.03 ± 63.86 [533.63–570.42]	553.24 ± 62.97 [535.10–571.38]	0.22	0.111	0.02
	High	562.65 ± 64.79 [543.98–581.31]	563.44 ± 63.88 [545.03–581.84]	0.14	0.303	0.01

Post hoc tests' outcomes with Bonferroni adjustments are presented for intraocular pressure (IOP) and central corneal thickness (CCT). Results are displayed as mean ± standard deviation [95% confidence interval] and percentage of change (Δ%). * and ** characterize statistically significant and highly statistically significant differences with the rest of the groups, respectively. [3]: significant differences with Group 3 (high baseline IOP). Cohen's d represents the effect size of the pre- and post-differences, with $d_{unb} < 0.50$ being a small effect, $0.50 \leq d_{unb} \leq 0.79$ a moderate effect, and $d_{unb} \geq 0.80$ a large effect.

Regarding the baseline IOP, significant differences were found in the post-exercise IOP values, as shown in Table 5. In fact, IOP variation (Δ%) showed significantly lower values in the participants with lower baseline IOP (≤14.00 mmHg) than those with higher IOP at baseline (≥17.00 mmHg; m.d. 1.60 mmHg, 95% CI [0.37–2.83], $p = 0.008$, $d_{unb} = 0.96$). The IOP variation (Δ%) in subjects with medium baseline IOP and those with higher IOP did not reflect statistical differences (m.d. 0.37 mmHg, 95% CI [0.28–1.87], $p = 0.420$, $d_{unb} = 0.18$). Furthermore, while subjects with moderate (between 14.01 and 16.99 mmHg) and higher baseline IOP displayed significant ($p \leq 0.001$) IOP decreases with moderate effect sizes (d_{unb} from 0.57 to 0.74), subjects with lower baseline IOP did not show statistically significant differences ($p = 0.114$) with a small effect size ($d_{unb} = 0.25$).

Differences in IOP variation (post-exercise minus pre-exercise) of each of the three groups of participants that were subdivided by IOP values can be found in Figure 1. It is worth mentioning that some subjects of the Lower-Tercile Group (baseline IOP under 14.00 mmHg) and a few of the Upper-Tercile group (baseline IOP over 17.00 mmHg) had their IOP increased due to the exercise effect, as can see in the boxplots on the left and right. Significant differences were encountered between the Lower- and Upper-Tercile Groups ($p = 0.008$, $d_{unb} = 0.96$).

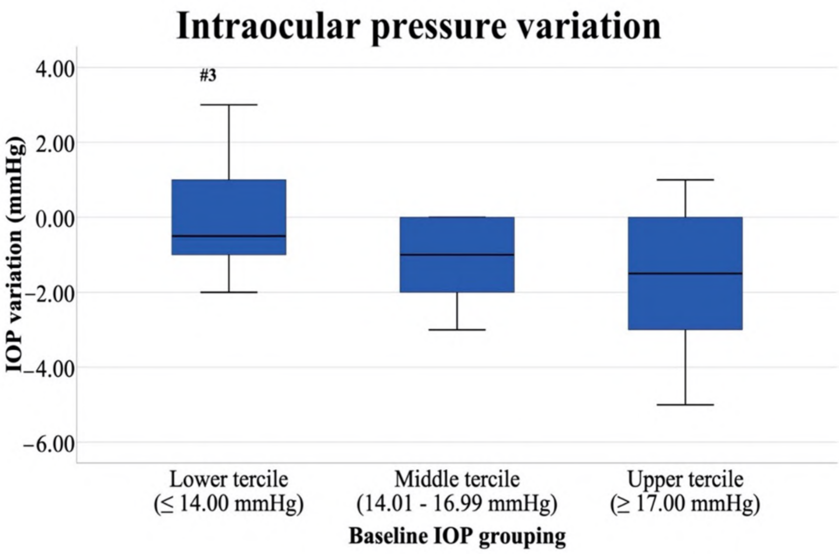

Figure 1. Intraocular pressure variation (post-exercise IOP minus pre-exercise IOP) of each of the three groups formed considering the baseline IOP levels (lower: $n = 18$; middle: $n = 17$; upper: $n = 14$). Values of the vertical axis (IOP variation) are presented in mmHg. The symbol "#3" highlights significant differences with the Upper-Tercile Group ($p = 0.008$, $d_{unb} = 0.96$).

3.2. Regression Analyses

Multiple linear regression was calculated to potentially predict the IOP variation based on different features of the sample (age, gender, levels of baseline IOP, and levels of baseline CCT). A significant regression equation was found ($F[3, 45] = 10.159$, $p < 0.001$, with an adjusted R^2 of 0.433). Baseline CCT and age were discarded from the equation due to non-significant results. The predicted variation of IOP was equal to 1.430 (sex)–0.270 (baseline IOP), where age is measured in years and the baseline IOP in mmHg. Regression analyses' models are displayed in Table 6, where the significant model and its coefficients are described. Model 2 was retained, as it was the one with the greatest prediction potential. This model predicted 43.3% of the variance in IOP. Sex and baseline IOP levels were significant ($p = 0.001$, and $p = 0.007$, respectively) predictors of the test outcomes. As shown in Table 6, while the baseline IOP levels were negatively correlated with the IOP variation, sex showed a positive correlation.

Table 6. Regression analyses.

Model	Predictor	Unstandardized Coefficients		Standardized Coefficients	*t*	Sig.	Adj. R^2	$\triangle R^2$	Durbin-Watson
		B	S.E.	β					
1	(Constant)	−2.799	1.035		−2.704	0.010	0.358	0.284	1.975
	Age	−0.036	0.026	−0.164	−1.392	0.171			
	Sex	1.800	0.372	0.569	4.835	0.000			
2 *	(Constant)	−0.606	3.059		−0.198	0.844	0.433	0.096	
	Age	−0.035	0.024	−0.158	−1.429	0.160			
	Sex	1.430	0.383	0.452	3.730	0.001			
	Baseline IOP	−0.270	0.096	−0.322	−2.817	0.007			
	Baseline CCT	0.005	0.005	0.104	0.892	0.377			

IOP: Intraocular pressure; CCT: Central corneal thickness; * Retained model; B = Unstandardized effect coefficient; S.E. = Standard Error; β = Standardized effect coefficient (Beta can be interpreted as controlling for the effects of other variables); t = Value of the Student's *t*-test; Sig = *p*-value of the test; Adj. R^2 = Adjusted R-square; $\triangle R^2$ = Changes in R-square.

4. Discussion

To the best of our knowledge, this is the first study aimed at evaluating the effect of an AG session on IOP. Additionally, a set of variables were selected to potentially predict the variation of IOP. The most notable findings were that a session of AG significantly reduced the IOP values, but did not significantly modify CCT (see Table 2), which is consistent with most previous studies on the effects of dynamic exercise on IOP [4,5,8] and confirms our first hypothesis. The small changes observed in CCT, such as those detected in females, could be due to physiological diurnal variations [47]. Additionally, it is worth highlighting that sex and baseline IOP levels were significant predictors of the fluctuation on IOP due to the exercise (see Table 6), which only partially confirms the second hypothesis. Accordingly, male gender and lower baseline IOP demonstrated in a previous study a possible association with visual field progression [48].

Bearing the aforementioned results in mind, it is worth discussing the outputs of this research under the light of other empirical evidence that addressed the influence of the independent variables selected in this study (sex, age, baseline IOP) on intraocular pressure. However, caution should be applied when comparing different methodologies of exercise and it should be borne in mind that the results presented in this study concern specifically acrobatic gymnastics.

First, sex could be a potential factor conditioning intraocular pressure due to sex hormones and genetic variants [49–51]. However, the findings encountered in the scientific literature are not consistent. Our results suggest that significant differences exist in both the baseline and post-exercise IOP values (see Table 3). Furthermore, while males had their IOP significantly modified due to the exercise effect, the intraocular pressure of females did not significantly change. This is in contrast with authors who encountered non-significant differences between sexes in the IOP changes due to treadmill running and isometric efforts [52,53]. On the other hand, the results presented concerning the sex of the participants are consistent with previous research that encountered differences between sexes [54–58] or identify sex as a confounding variable in the relationship between exercise and glaucoma [59]. More specifically, Vera et al. [60] detected further IOP fluctuations in males compared with women after isometric squats. Further research needs to be done in this regard eliminating confounding variables to elucidate if there is an actual difference in the IOP response to exercise between sexes and the origin of these differences.

Age has been widely studied as a conditioning factor of the IOP with significant positive correlations [6,52,55,61]: Only one study was found reporting non-significant correlations between age and IOP [62]. The age of 40 is recognized by the American Academy of Ophthalmology as the cutoff criterion to start comprehensive medical eye evaluation screening [63]. Due to this, only subjects under 40 years old were selected for the study. Although age was excluded from the prediction equation and was not correlated with IOP variations, significantly different behaviors were observed in the IOP of young adults under 25 years old and adults over 25. The fact of not finding a significant correlation with age in the present study could be due to the age of the sample being limited to subjects under 40 years, with studies reporting that the significant increase in baseline values occurs after the age of 40 [64]. This is interesting and coincides with the information presented in Table 4. While the baseline IOP of both groups (under 40 years old) was not significantly different, the after-exercise IOP showed significant between-group differences with a moderate effect size (d_{unb} = 0.50). These results suggest that once finished with the effort, the young adults under 25 years old return faster to pre-exercise values than adults over 25 years old. This could be due to the compensatory mechanisms in charge of maintaining tissue stability [2], which may function better in younger subjects, as demonstrated in rats [65].

As for the third independent variable included in this study, it is worth highlighting that IOP followed different behaviors in subjects with medium and high baseline IOP compared to subjects with lower baseline IOP (see Table 5). This is consistent with previous research that encountered larger fluctuations in subjects with higher baseline IOP and less pronounced fluctuations in subjects with lower baseline IOP [2,7,66]. More specifically, larger post-exercise decreases in subjects with higher pre-test values are reported by the expert literature [54,67–69]. In contrast, one study encountered a negative significant correlation between baseline IOP and its change (elevation) after an incremental running test [70] and other non-significant correlations [71]. The results presented are to be considered of relevance, bearing in mind that subjects with lower IOP are more susceptible to optical nerve damage with fluctuations [7,48]. It could be stated that the baseline level of IOP influences the post-exercise IOP and, therefore, this should be a factor to consider in the management of subjects with glaucoma risk factors.

Finally, the analysis and comparison with animal studies could shed some light on the behavior of IOP with exercise. For instance, Castro et al. [72] found positive results in the IOP of rats on a high-fructose diet with treadmill exercise at low intensity. These authors proposed as potential underlying mechanisms improved insulin sensitivity, reduced arterial pressure, and diminished peripheral sympathetic modulation [72]. Additionally, one study reported that swimming can reverse the negative impact of aging on the optic nerve function of rats [73]. As reported by previous expert literature, exercise-related IOP diminishments could be related to lower norepinephrine concentrations, increased colloid osmotic pressure, co-action of nitric oxide and endothelin after exercise, and the association with a β2-adrenergic receptor gene polymorphism [74–76]. Future studies should evaluate the specific mechanisms that led to lower post-exercise IOP with AG.

Limitations and Future Directions

Although all the procedures carried out in this study were carefully designed and supervised, several limitations should be listed. Validated non-contact air-puff tonometry was chosen as it is easy to use and does not require the use of anesthesia [77,78]. However, one should bear in mind that the values presented in this study only reflect pre- and post-exercise values. In this regard, continuous monitoring devices [79] would provide the scientific literature with relevant information on what exactly happens during the practice. Additionally in this concern, future studies should address the time needed for IOP to return to pre-exercise values with similar exercise procedures. As per the results on the different IOP behaviors depending on the age of subjects, it could be interesting to include adults over 40 years in a similar study design. Finally, and as presented in the introduction, the importance of field-based studies like this is unnegotiable; however, it could be of great scientific interest to continuously monitor IOP while performing somersaults and/or tumbling skills in a controlled laboratory environment.

5. Conclusions

In summary, IOP significantly decreased and CCT remained unchanged from pre- to post-exercise. The IOP of males was lowered from baseline to the end of the study. On the other hand, females did not reflect IOP changes. Similarly, the IOP of adults was further reduced compared to young adults. Finally, subjects with higher IOP at baseline (middle and upper terciles) had more pronounced decreases than the participants with lower IOP. Sex and baseline intraocular pressure were obtained as significant predictors of IOP variation.

Taken together, the analyses presented in this article shed some light on the behavior of specific ocular parameters after exercise. The combination of findings presented herein could be of interest for the programming of physical exercise for gymnastics coaches and ophthalmologists or optometrists in the prevention, management, and control of risk factors associated with IOP and glaucoma.

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9.1.2 Article 2

Proceeding

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A systematic review on the muscular activation on the lower limbs with five different variations of the squat exercise

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ABSTRACT

The squat is one of the most commonly used resistance exercises for performance and health due to its biomechanical and neuromuscular similarities to a wide range of athletic and everyday activities. There is a large number of squat variations (based on the descent depth, width of the stance, bar placement) with significant biomechanical and neuromuscular differences between them. The aim of this study was to systematically review the scientific literature to gather data on the muscular activation of the lower limb during different variants of the squat exercise. High-bar squat (full range of motion, to parallel and partial range of motion), low-bar squat, front squat, overhead squat and guided squat on Smith machine were included in the analysis. 30 articles met the inclusion criteria and were reviewed. Quality of the included studies was analysed with the PEDro scale. Main findings were that in the squat exercise activation of the knee-extensors is predominant. However, different activation patterns were observed with different distances between the feet, different depths, hips rotation or flexion, intensities. For instance, low-bar squat involves a greater hip hinge and thus, provokes major activation on the hip-extensors than other squat variations. It is worth highlighting that similar activation patterns were observed between the front squat and the high-bar squat. The variation with least activation was the guided squat. The evidence presented in this study may help the strength and conditioning professionals and practitioners with the exercise selection depending on the muscular targets and the individual characteristics of the athlete.

Keywords: Electromyographic activity; Resistance exercise; Quadriceps; Gluteus; Hamstrings; Calves.

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INTRODUCTION

The squat is one of the most commonly used resistance exercises for performance and health due to its biomechanical and neuromuscular similarities to a wide range of athletic and everyday activities (Andersen et al., 2016; Clark et al., 2012; Kompf & Arandjelović, 2017; Schoenfeld, 2010). All variants of the squat involve synergistic hip, knee, and ankle flexion in the descent, followed by knee and hip extension in the ascent which finishes with the individual in the starting position (Clark et al., 2012; Escamilla et al., 2001; Iversen et al., 2017; Schoenfeld, 2010; Vigotsky et al., 2019). However, there is a large number of squat variations (based on the descent depth, the width of the stance, bar placement, orientation of the knee flexion planes, and so on) with significant biomechanical and neuromuscular differences between them (Clark et al., 2012; Kompf & Arandjelović, 2017; Schoenfeld, 2010; Van den Tillaar et al., 2014). One of the aims of the expert research to the date has been to enlighten the strength and conditioning professionals and athletes with the differences between these variations in terms of muscular activity (Bourne et al., 2017). Understanding the muscular activity of each exercise is a key point in the prescription and programming of resistance exercises depending on the individual characteristics (Bolgla & Uhl, 2005; Borreani et al., 2014; Neto et al., 2020).

Muscular activity is often measured with surface electromyography, a method that registers the intensity and duration of electric signals produced in the muscles (Chowdhury et al., 2013). Electrodes are placed on specific superficial points that cover the muscle to analyse. The electromyograph gives raw data in absolute electric signal intensity in millivolts (mV) or microvolts (μV). Typical methods to standardize the results are a) as a relative percentage of a maximum voluntary isometric contraction (IMVC); b) as a relative percentage of the maximum historical contraction (MVC); c) as the square root of the average power of the EMG signal for a given period of time (root mean square; RMS) (Sinclair et al., 2015). Data in the scientific literature are uneven and thus, comparisons between studies are sometimes difficult.

The main objective of this research was to systematically review the expert literature to gather data on the muscular activation of the lower limb during different variants of the squat exercise. We aimed to identify the main characteristics of each variant, the predominant muscle groups involved, and to determine the variant with higher activation levels, through the analyses of the included studies.

METHODS

For this systematic review, the protocols of the PRISMA declaration (Hutton et al., 2015; Urrútia & Bonfill, 2010) were followed.

Search strategy

Four databases (Web of Science, PubMed, Scopus, and SportDiscus) and ProQuest (i.e. an electronic tool containing doctoral thesis) were consulted to collect information about muscular activation. Also, the Strength and Conditioning Journal was consulted. No temporal restrictions were used in the search. The following terms were used: ["*squat*" OR "*squat exercise*" OR "*high bar squat*" OR "*low bar squat*" OR "*overhead squat*" OR "*front squat*"] AND ["*EMG*" OR "*electromyography*" OR "*electromyographic activity*" OR "*muscle activation*" OR "*muscle activity*"]. A third line was added with the following terms to include technical variations: ["*stance width*" OR "*hip rotation*" OR "*Smith machine*" OR "*deep*" OR "*depth*" OR "*parallel*" OR "*partial*" OR "*quarter*"]. Furthermore, the operator "*NOT*" was used in combination with the terms "*balance*", "*instability*", "*unstable*", "*bands*", "*chains*", "*injury*", "*injured*", "*unload*", and "*therapeutic*" to refine the results and exclude articles that did not follow the inclusion criteria.

Eligibility criteria

Studies that examined muscle activation on the lower limb in squats written in Spanish or English were included in the analyses. Inclusion criteria were a) including healthy subjects with no recent history of injury; b) using stable surfaces to perform the squats; c) using a barbell with load. On the other hand, exclusion criteria were a) using variable resistance (i.e. elastic bands, chains) to load the exercise; b) analysing muscle activity of the upper limb or trunk; c) performing an isometric squat.

Article selection and data processing

Studies

Screening of titles and abstracts was initially carried out to identify potentially relevant studies. A standardized form was used to assess the eligibility of each article considering the inclusion-exclusion criteria. Figure 1 shows the flow diagram that summarizes the study selection process after the reading of the titles and abstracts of the initial search.

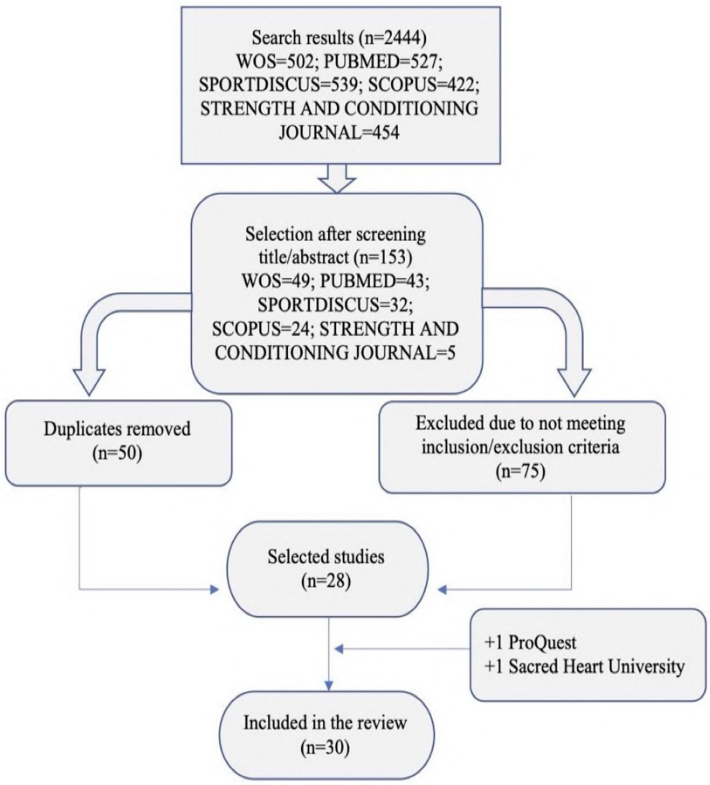

Figure 1. Flow diagram that summarizes the study selection process from the first search to the final selection.

Squat variations

After carefully reading the selected articles five squat variations were selected for the analysis by agreement between the authors. Some squat variations found in the literature and excluded from the analysis were the unilateral squat, Bulgarian squat, and wall squat. The five squat variations included were (see Figure 2):

High-bar squat (26 studies): the bar is placed across the shoulder on the trapezius, slightly above the level of the acromion and the posterior aspect of the deltoids (Schoenfeld, 2010; Vigotsky et al., 2019; Wretenberg et al., 1996).

Front squat (5 studies): the bar is held in front of the chest at the clavicle (Bautista, 2019; Schoenfeld, 2010).

Overhead squat (2 studies): bar is held with both hands, fully extended elbows, and externally rotated shoulders (Bautista, 2019).

Guided squat on Smith machine (2 studies): the bar is guided and thus, it only can be moved up and down (different variations of the squat can be performed on the Smith machine, however for this study, we considered a high bar squat; Clark et al., 2012).

Low-bar squat (1 study): the bar is placed slightly below the level of the acromion (Schoenfeld, 2010; Wretenberg et al., 1996).

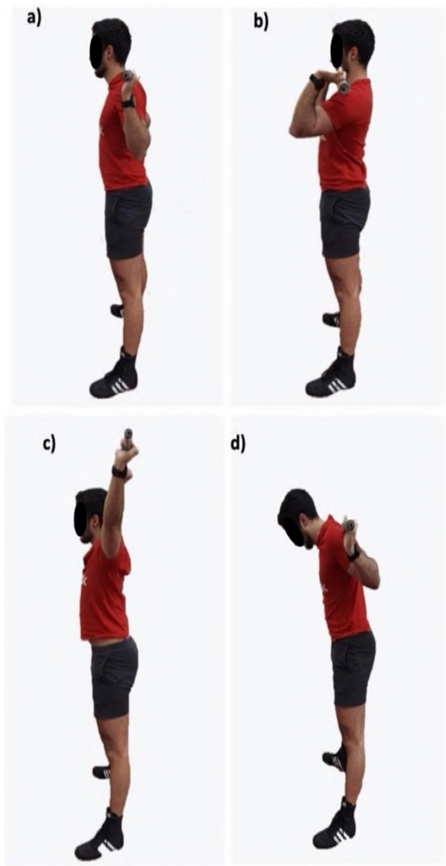

Figure 2. From left to right: a) high-bar squat, b) front-squat, c) overhead squat, d) low-bar squat. The guided squat is not pictured as for this study, the placement of the bar was the same as in the high-bar squat.

The high bar squat was in turn divided in full range of motion (ROM; i.e. the hips are lower than the knees), to parallel (i.e. lowering until the femur is parallel to the ground, approximately 90º of knee movement), and partial range of motion (i.e. half the ROM of a parallel squat, a quarter of a full ROM squat, approximately 45º of knee movement). Also, different technical variants of the squat exercise such as stance width and hip rotation planes were included to enrich the analyses.

Muscles analysed

As mentioned in the objective, this study focuses on the muscles of the lower limb. After a thorough reading of the selected articles, the authors selected the muscles to be included in the analysis. These muscles were a) gluteus maximus, b) gluteus medialis, c) hip adductors, d) vastus lateralis, e) vastus medialis, f) rectus femoris, g) biceps femoris, h) semitendinosus, i) tibialis anterior, j) gastrocnemius and k) soleus. Muscles "*a, b, and c*" act mainly on the hips; muscles "d, e, and f" are part of the quadriceps and are mainly involved in the knee-extension; muscles "*g and h*" are part of the hamstrings and their contraction mainly affect the knees; the tibialis anterior (muscle "*i*") is an ankle dorsiflexor; and finally, the muscles "*j and k*" are part of the calves and their action provoke an ankle extension. Previous expert literature (Netter, 1999) can be consulted for further information on the included muscles and anatomy.

Electromyographic values

EMG values are unequally reported among the expert literature, not only on the units used (millivolts, microvolts, percentage of isometric maximum voluntary contraction, percentage of maximum voluntary contraction, percentage of root mean square values) but also on the measured phase (concentric and eccentric, mean of the set, mean of a repetition). In this review, the authors standardized the values when possible to facilitate the comprehension and the comparison between studies. For instance, values in millivolts were transformed into microvolts. Also, results of concentric and eccentric phases were averaged to obtain a single value.

Quality assessment

The quality of the included studies was analysed using the PEDro scale (Maher et al., 2003). The scale was modified to fit the design of the included studies (see Table 3). Points 2 and 3 were unified into one point that assessed the randomization of the exercise conditions performed. Point 4 had to be excluded due to not including studies with control and experimental groups. Finally, points 5, 6, and 7 were also excluded due to the impossibility of blinding subjects or researchers. The resultant scale to evaluate the quality of the articles was composed of 6 items.

RESULTS

30 articles met the inclusion criteria and were reviewed (Figure 1). As abovementioned (see "*data processing and analysis-squat variations*" section), the most widely studied variation of the squat exercise was the high-bar squat (26 studies), followed by the front-squat (5 studies), the overhead squat, and guided squat (both analysed by 2 studies), and finally the low-bar squat (1 study). The main muscular group involved in all the variations was the quadriceps, with some differences between each squat variation, and also between different technical modifications (i.e. ROM, stance width, hip rotation, feet placement).

Due to the considerable amount of variations and exercise conditions, the results section will be divided into six subsections: one for each squat variation, and one including the technical modifications of the exercise (i.e. stance width, hip rotation). Furthermore, Table 1 includes the main characteristics of the included studies (i.e. sample characteristics, exercise condition, measured muscles, and main results), and Table 2 presents reported EMG values. EMG values are presented in different units (i.e. absolute values, IMVC, MVC, RMS), and thus caution should be applied when comparing values between studies.

High-bar squat
A major part of the studies found the main activity on the vastus lateralis, vastus medialis, and rectus femoris, in this order (Aspe & Swinton, 2014; Contreras et al., 2015, 2016; da Silva et al., 2017; Delgado et al., 2019; Ebben et al., 2009; Eliassen et al., 2018; Gorsuch et al., 2013; Hammond et al., 2016; Iversen et al., 2017; Korak et al., 2018; Robbins, 2011; Schwanbeck et al., 2009; Wu et al., 2019; Yavuz et al., 2015). Only one study found major activation on the biceps femoris than on each of these three aforementioned muscles (Andersen et al., 2014). Regarding the activation on the gluteus and hamstrings, while some authors observed a greater activation on the gluteus maximus (Caterisano et al., 2002; Fauth et al., 2010; McCurdy et al., 2018), others reported a higher activity on the hamstrings (Andersen et al., 2014; Delgado et al., 2019; Gullett et al., 2009). Only three authors reported activation levels on the muscles of the calves when performing a high-bar squat (Aspe & Swinton, 2014; da Silva et al., 2017; Schwanbeck et al., 2009).

Front squat
Muscle activity in this squat variation followed similar patterns to other squat variations (i.e. major activation on the vastus lateralis and medialis). Korak et al. (2018) reported similar activation levels on the rectus femoris and gluteus maximus. Opposite to the aforementioned authors, Gullet et al. (2009) found higher activation levels on the hamstrings (semitendinosus: 140% of the IMVC) than on the quadriceps (vastus lateralis: 60% of the IMVC; vastus medialis: 81% of the IMVC; rectus femoris: 59% of the IMVC).

Overhead squat
Two studies analysed this variation of the squat exercise (Aspe & Swinton, 2014; Bautista, 2019). As happened with the rest of the variations, major activation levels were found on the vastus lateralis in both studies. As secondary muscles, Aspe & Swinton (2014) reported higher activation levels on the gluteus (61% of the MVC) than on the biceps femoris (54% of the MVC). Bautista (2019) found lower activation levels on the biceps femoris (31% of the IMVC) but did not analyse the gluteus maximus.

Guided squat on Smith machine
In one study, activation patterns were the same as those reported in the high-bar squat (Schwanbeck et al., 2009). In the study of Blanpied et al. (1999) major activation levels were observed on the gluteus maximus than on the quadriceps or the hamstring. The effects of a technical modification (i.e. feet placed in line with the body or ahead) when performing a guided squat are presented in the following section.

Low-bar squat
The study of McCaw and Melrose (1999) was the only one that analysed the activation levels in a low-bar squat and met the eligibility criteria. The main activity was observed on the vastus lateralis and medialis, followed by the rectus femoris. Lower activity on the hip adductors and gluteus in comparison to the quadriceps was observed, the activity of these last two muscles being similar. The lowest activation levels were detected on the biceps femoris. Further analyses of this squat variation were based on technical modifications as shown further below (see "*technical modifications*" section).

Technical modifications
Range of motion
The comparison between three different depths (i.e. partial, parallel, and full squats) yielded similar activation patterns, with controversial results observed on the gluteus activation. While Caterisano et al. (2002)

Table 1. Characteristics of the included studies (N = 30).

(Author, year)	Sample (N, sex, age characteristics)	Exercise/s	Load	Measured muscles	Main results
(Bautista, 2019)	7 trained males Age: 28.0±3.6 years Height: 175.0±5.3cm Weight: 92.0±26.1kg	- Front squat - Overhead squat	3R at 65%, 80% and 95% of 3RM	- Vastus lateralis - Biceps femoris	Major activity on the vastus lateralis in the concentric phase of the front squat, being this major activity on the vastus lateralis in the eccentric phase of the overhead squat.
(Delgado et al., 2019)	8 trained males Age: 25.0±3.3 years Height: 177.7±6.6cm Weight: 84.0±6.5kg Minimum experience: 1 year	- Full ROM high-bar squat	1RM	- Gluteus maximus -Vastus lateralis - Biceps femoris	Major activity on the vastus lateralis.
(Wu et al., 2019)	19 trained males Age 22.1±1.1 years Height: 174.4±5.2cm Weight:76±13.3kg	- High-bar squat to parallel	10R with 20kg	- Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus - Tibialis anterior - Gastrocnemius	Major activity on the vastus lateralis and medialis.
(Korak et al., 2018)	13 females Age: 22.8±1.0 years Height: 166.4±4.2cm Weight: 73.4±14kg Minimum experience: 1 year	- High-bar squat to parallel - Front squat to parallel	3R at 75%1RM	- Gluteus maximus - Vastus medialis - Rectus femoris - Biceps femoris	- Back squat: Major activation on the rectus femoris, vastus lateralis, and vastus medialis. - Front squat: Major activation on the vastus lateralis, vastus medialis, rectus femoris, and gluteus maximus.
(Eliassen et al., 2018)	14 trained males Age: 23.0±4.0 years Height: 181.0±6.0cm Weight: 80.5±8.5kg	- High-bar partial squat	4RM	- Gluteus maximus - Gluteus medialis - Vastus lateralis - Vastus medialis - Rectus femoris - Biceps femoris - Semitendinosus - Gastrocnemius	Major activity on the rectus femoris, vastus lateralis, and vastus medialis.
(McCurdy et al., 2018)	18 females Age: 20.9±1.1 years Height: 165.0±5.5cm Weight: 61.8±6.4kg Minimum experience: 1-5years	- High-bar squat to parallel	3R at 8RM load	- Gluteus maximus - Hamstrings	Major activation on the gluteus maximus.

(Iversen et al., 2017)	12 males and 12 females Age: 25.0±3.0 and 25.0±2.0 years	- High-bar squat to parallel	3R at 10RM load	- Gluteus maximus - Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus	Major activation on the vastus medialis and lateralis.
(da Silva et al., 2017)	15 males Age: 26.0±5.0 years Height: 173.0±6.0cm	- High-bar squat to parallel - Full ROM high-bar squat	10RM	- Gluteus maximus - Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus - Soleus	Major activity on the vastus lateralis and medialis, and rectus femoris. Similar activation patterns in both high-bar squat variants.
(Contreras et al., 2016)	13 females Age: 28.9±5.1 years Height: 164.0±6.3cm Weight: 58.2±6.4kg	- High-bar squat to parallel - Full ROM high-bar squat - Front squat	10RM	- Gluteus maximus - Vastus lateralis - Biceps femoris	Major activation on the vastus lateralis in all the three variations of the squat exercise.
(Hammond et al., 2016)	8 males Age: 21.0±1.0 years Height: 176.0±5.0cm Weight: 80.0±9.0kg Minimum experience 5.0±1.0 years	- High-bar partial squat - High-bar squat to parallel - Full ROM high-bar squat	5RM	- Gluteus maximus - Vastus medialis - Vastus lateralis - Biceps femoris	- Major activation on the vastus medialis and vastus lateralis in all the three variants of the exercise. - Minor general muscle activity in the partial squat.
(Contreras et al., 2015)	13 females Age: 28.9±5.1 years Height: 164.0±6.3cm Weight: 58.2±6.4kg	- High-bar squat to parallel	10RM	- Gluteus maximus - Vastus lateralis - Biceps femoris	Major activation on the vastus lateralis.
(Yavuz et al., 2015)	19 women, 9 men, 21.5 63 years, 170 68.4 cm, 65.7 611.8 kg 19 women, 9 men, 21.5 63 years, 170 68.4 cm, 65.7 611.8 kg 12 males Age: 21.2±1.9 years	- High-bar squat to parallel - Front squat	1R at 90%1RM	- Gluteus maximus - Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus	Major activation on the vastus medialis and vastus lateralis in both exercises. Secondary activation on: - Back squat: Gluteus maximus and rectus femoris. - Front squat: Rectus femoris.
(Aspe & Swinton, 2014)	14 males Age: 26.0±7.0 years Height: 182.5±13.5cm Weight: 90.5±17.5kg	- Full ROM high-bar squat - Overhead squat	3R at 60%, 75% and 90% of 1RM	- Gluteus maximus - Vastus lateralis - Biceps femoris - Gastrocnemius	Major activity on the vastus lateralis in both squat variations.

(Van den Tillaar et al., 2014)	15 trained males Age: 24.0±4.0 years Height: 179.0±6.0cm Weight: 82.0±11.0kg Minimum experience: 6.0±3.0 years	- High-bar squat to parallel	6RM	- Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris	Major activity on the vastus lateralis and vastus medialis.
(Andersen et al., 2014)	15 trained males Age: 24.0±4.0 years Height: 179.0±6.0cm Weight: 82.0±11.0kg Minimum experience: 6.0±3.0 years	- High-bar squat to parallel	6RM	- Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Soleus	Major activation on the biceps femoris.
(Gorsuch et al., 2013)	10 males and 10 females Age: 19.2±0.4 and 19.9±0.4 years Height: 176.8±1.5 and 166.7±1.5cm Weight: 66.2±2.5 and 55.9±1.4kg	- High-bar squat to parallel - High-bar partial squat	6R at 10RM load	- Rectus femoris - Biceps femoris - Gastrocnemius	Major activation on rectus femoris in both exercises.
(Lynn & Noffal, 2012)	15 males and 16 females Age: 23.1±2.1 years Height: 170.0±11.0cm Weight: 71.0±17.3kg	- Full ROM high-bar squat	As many repetitions in one minute	- Gluteus maximus - Rectus femoris - Biceps femoris	Major activation on the rectus femoris and vastus.
(Robbins, 2011)	10 males Age: 24.0±1.2 years Height: 177.0±5.0cm Weight: 82.2±10.2kg	- High-bar squat to parallel	3R at 85%1RM	- Gluteus maximus - Vastus medialis - Biceps femoris - Gastrocnemius	Major activation on the vastus medialis.
(Pereira et al., 2010)	5 males and 5 females Age: 21.0±1.0 years Height: 171.4±9.4cm Weight: 66.5±11.4kg	- High-bar squat to parallel (three hip rotations)	10RM	- Hip adductors - Rectus femoris	The more external rotation more activation on the hip adductors, but no changes on rectus femoris.
(Fauth et al., 2010)	16 females Age: 21.2±2.2 years Height: 169.4±7.5cm Weight: 66.1±9.9kg	- Full ROM high-bar squat	2R at 6RM load	- Gluteus maximus - Gluteus medialis - Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus	Major activation on the vastus lateralis and medialis, and gluteus maximus.

(Ebben et al., 2009)	11 males and 9 females Age: 21.5±1.9 and 20.0±1.5 years Weight: 78.9±9.6 and 66.4±7.5kg	- Full ROM high-bar squat	2R at 6RM load	- Vastus lateralis - Rectus femoris - Biceps femoris	Major activation on the vastus lateralis and rectus femoris.
(Schwanbeck et al., 2009)	3 males and 3 females Age: 22.0±1.2 years Height: 171.0±12.0cm Weight: 71.5±12.7kg Minimum experience: 2-5 years	- Guided squat on Smith machine - High-bar squat to parallel	8RM	- Vastus medialis - Vastus lateralis - Biceps femoris - Tibialis anterior - Gastrocnemius	Major general activation in the free-weight squat than in the guided squat. Major activation on the vastus lateralis and medialis in both variations of the squat exercise
(Gullett et al., 2009)	9 males and 6 females Age: 22.1±3.6 years Height: 171.2±6.4cm Weight: 69.7±6.2kg	- High-bar squat to parallel - Front squat	3R at 70%1RM load	- Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus	No significant differences in muscle activity between both variations. Major activation on the semitendinosus, vastus lateralis, rectus femoris, and vastus lateralis, in this order.
(Paoli et al., 2009)	6 trained males Age: 25.8±3.7 years Height: 182.0±3.5cm Weight: 83.2±5.8kg	- High bar squat	3S 10R: 1) with no weight 2)30%RM 3)70%RM (3SW: normal, x1.5 & x2)	- Gluteus maximus - Gluteus medialis - Hip adductor - Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus	Major activation was observed in vastus medialis, vastus lateralis, and rectus femoris in the 3 stance widths.
(Caterisano et al., 2002)	10 males Age: 24.3±5.6 years Height: 182.6±6.9cm Weight: 86.1±11.2kg Body fat: 6.1±1.8% Minimum experience: 5 years	- High-bar partial squat - High-bar squat to parallel - Full ROM high-bar squat	3R at between 100-125% of body-weight	- Gluteus maximus - Vastus medialis - Vastus lateralis - Biceps femoris	- High-bar partial squat: Major activation on the vastus medialis and lateralis. - High-bar squat to parallel: Major activity on the vastus medialis and lateralis, with higher activity on the gluteus compared to partial. - Full ROM high-bar squat: Major activation on the gluteus in the concentric phase, and on the vastus medialis and lateralis in the eccentric.
(Escamilla et al., 2001)	10 males Age: 29.6±6.5 years Height: 177.0±8.5cm Weight: 93.5±14.0kg Minimum experience: 10.1±7.7years	- High-bar squat to parallel Stance width: narrow and wide.	12RM	- Vastus medialis - Vastus lateralis - Rectus femoris - Semitendinosus - Semimembranosus - Gastrocnemius	Major activation on the vastus medialis, vastus lateralis, and rectus femoris, in this order. No statistical difference between these muscles.

(Boyden et al., 2000)	6 males Age: 23.0±4.1 years Height: 180.0±3.0cm Weight: 80.95±1.5kg	- High-bar squat to parallel (four different hip rotations)	3R at 65% and 75%1RM	- Vastus medialis - Vastus lateralis - Rectus femoris	Major activation at 75%1RM. No significant differences between the hip rotations.
(Wright et al., 1999)	6 football players and 5 bodybuilders	- Full ROM high-bar squat	3R at 75%1RM	- Biceps femoris - Semitendinosus	No statistical difference between both muscles.
(Blanpied, 1999)	20 females Age: 31.3±6.9 years Height: 160.9±4.1cm Weight: 58.1±8.7kg	- Guided squat on Smith machine	5R, feet in line with the body (IL) and placed forward (FF)	- Gluteus maximus - Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris - Semitendinosus	- FF: Major activation on the gluteus and biceps femoris, semitendinosus, and semimembranosus. - IL: Major activation on the gluteus and vastus medialis, vastus lateralis, and rectus femoris.
(McCaw & Melrose, 1999)	9 males Age: 22.0±1.0 years Height: 183.0±8.0cm Weight: 92.0±14.0kg Minimum experience: 7.0±2.0 years	- Low-bar squat	5R at 60-75%1RM, SW: closed, normal, and open	- Gluteus maximus - Hip adductor - Vastus medialis - Vastus lateralis - Rectus femoris - Biceps femoris	Major activation on the vastus lateralis, vastus medialis, rectus femoris, and adductor longus with increasing load. Major activation on the gluteus with increasing foot-width.

Age, height, weight, and minimum experience values are presented as Mean ± Standard Deviation. ROM: Range of Motion; S: Sets; R: Repetition/s; RM: Repetition/s Maximum; SW: Stance Width; IL: feet in-line with the boy: FF: Forward placed Feet.

Table 2. Electromyographic activity reported in each study.

(Author, year)	**EMG value**	**Squat**	**Measured muscles**										
			GM	GMed	HA	VL	VM	RF	BF	ST	TA	GN	SL
(Bautista, 2019)	% IMCV	Front squat	-	-	-	69.6±4.5	-	-	24.3±5.1	-	-	-	-
		Overhead squat	-	-	-	67.6±7.8	-	-	24.3±5.1	-	-	-	-
(Delgado et al., 2019)	Raw (μV)	High-bar squat (F)	~145	-	-	~350	-	-	~160	-	-	-	-
(Wu et al., 2019)	% MVC	High-bar squat (P)	-	-	-	70.2±24.8	66.4±24.4	39.5±15.7	12.9±14.9	11.8±5.3	30.5±11.1	9.8±5.1	-
(Korak et al., 2018)	% MVC	High-bar squat (P)	~80	-	-	~97	~96	~102	~78	-	-	-	-
		Front squat	~94	-	-	~102	~98	~101	~81	-	-	-	-
(Eliassen et al., 2018)	Raw (μV)	High-bar squat (Q)	130.5±25.0	120.5±12.5	-	308±33	260±36	231.5±34	92.5±14.8	70.5±11.0	-	61.5±11.5	88.0±11.0

(McCurdy et al., 2018)	% IMVC	High-bar squat (P)	41.5±18.4	-	-	-	-	-	Hamstrings: 24.5±9.6		-	-	-
(Iversen et al., 2017)	% MVC	High-bar squat (P)	~33	-	-	~55	~65	~39	~14	~15	-	-	-
(da Silva et al., 2017)	% IMVC	High-bar squat (P)	~20	-	-	~60	~48	~60	~35	~30%	-	-	~30
		High-bar squat (F)	~15	-	-	~58	~48	~70	~30	~35	-	-	~25
(Contreras et al., 2016)	% IMVC	High-bar squat (P)	37.5±20.0	-	-	110.3±47.2	-	-	14.9±6.6	-	-	-	-
		High-bar squat (F)	35.9±18.9	-	-	123.8±67.4	-	-	14.4±6.4	-	-	-	-
		Front squat	36.6±17.6	-	-	124.2±72.9	-	-	13.1±4.7	-	-	-	-
(Hammond et al., 2016)	% IMVC	High-bar squat (Q)	~15	-	-	~34	~39	-	~9	-	-	-	-
		High-bar squat (P)	~18	-	-	~37	~48	-	~14	-	-	-	-
		High-bar squat (F)	~15	-	-	~35	~48	-	~13	-	-	-	-
(Contreras et al., 2015)	% IMVC	High-bar squat (P)	37.4±20.0	-	-	110.4±47.2	-	-	14.9±6.6	-	-	-	-
(Yavuz et al., 2015)	% IMVC	High-bar squat (P)	37.1±23.5	-	-	47.0±15.1	48.8±14	36.7±12.4	26.2±16.1	21.5±12.0	-	-	-
		Front squat	37.2±27.0	-	-	51.2±17.3	55.4±18	46.1±21.7	24.1±25.4	16.0±9.0	-	-	-
(Aspe & Swinton, 2014)	% MVC	High-bar squat (F)	60% RM: 43.2±27.1 75% RM: 54.9±28.7 90% RM: 58.4±31.1	-	-	60%RM: 69.1±22.7 75%RM: 75.3±25.3 90%RM: 79.1±55.6	-	-	60%RM: 42.5±20.8 75%RM: 49.8±24.6 90%RM: 52.1±24.9	-	-	60% RM: 35.4±18.7 75% RM: 44.0±28.6 90% RM: 47.0±29.9	-
		Overhead squat	60% RM: 31.7±17.7 75% RM: 40.2±20.5 90% RM: 39.8±21.1	-	-	60%RM: 62.2±21.4 75%RM: 68.0±22.4 90%RM: 70.4±23.1	-	-	60%RM: 36.2±20 75% RM: 42.1±20.6 90% RM: 44.5±26.2	-	-	60% RM: 36.4±20.5 75% RM: 34.8±16.6 90% RM: 36.4±14.7	-

(Van den Tillaar et al., 2014)	RMS (µV)	High-bar squat (P)	-	-	-	~610	~600	~400	~180	-	-	-	-
(Andersen et al., 2014)	% IMVC	High-bar squat (P)	-	-	-	~80	~80	~90	~110	-	-	-	~95
(Gorsuch et al., 2013)	Raw (µV)	High-bar squat (P)	-	-	-	-	-	~180	~180	-	-	~50	-
		High-bar squat (Q)	-	-	-	-	-	~140	~70	-	-	~50	-
(Lynn & Noffal, 2012)	% MVC	High-bar squat (F)	20±14.2	-	-	-	-	64.4±44.5	20.6±21.9	-	-	-	-
(Robbins, 2011)	% MVC	High-bar squat (P)	~38	-	-	-	~81	-	~23	-	-	~40	-
(Pereira et al., 2010)	% IMVC	High-bar squat (P)	-	-	HER 0º: ~14 HER 30º: ~20 HER 50º: ~20	-	-	HER 0º: ~41 HER 30º: ~47 HER 50º: ~41	-	-	-	-	-
(Fauth et al., 2010)	% IMVC	High-bar squat (F)	90±42	26±13	-	114±54	133±52	81±35	45±20	37±25	-	-	-
(Ebben et al., 2009)	% IMVC	High-bar squat (F)	-	-	-	~90	-	~78	~37	-	-	-	-
(Schwanbeck et al., 2009)	% MVC	Guided squat	-	-	-	~60	~60	-	~18	-	~30	~20	-
		High-bar squat (P)	-	-	-	~80	~81	-	~20	-	~59	~30	-
(Gullett et al., 2009)	% IMVC	High-bar squat (P)	-	-	-	~61	~80	~62	~20	~130	-	-	-
		Front squat	-	-	-	~60	~81	~59	~19	~140	-	-	-
(Paoli et al., 2009)	% RMS	High-bar squat (P)	NW: 20.5±5 x1.5: 24.1±9 x2: 28.8±7	NW: 25.2±7 x1.5: 26.5±7 x2: 31.8±12	NW: 17.0±5 x1.5: 16.6±7 x2: 16.9±6	NW: 60.5±7 x1.5: 59.7±9 x2: 66.0±11	NW: 57.3±7 x1.5: 57.5±9 x2: 53.2±15	NW: 57.1±8 x1.5: 50.4±8 x2: 51.6±0.1	NW: 24.5±3 x1.5: 25.6±6 x2: 27.2±7	NW: 23.2±7 x1.5: 23.8±10 x2: 25.4±11	-	-	-
(Caterisano et al., 2002)	% MVC	High-bar squat (Q)	~15	-	-	38.6±12.3	35.4±13.3	-	~11	-	-	-	-

		High-bar squat (P)	~19	-	-	38.4±12.9	31.1±9.7	-	~11	-	-	-	-
		High-bar squat (F)	~24	-	-	32±10.5	31.7±10.3	-	~12	-	-	-	-
(Escamilla et al., 2001)	% IMVC	High-bar squat (P)	-	-	-	NS: 39.5±7 WS:40±7	NS: 42±8 WS:41.5±5	NS: 32±13.5 WS: 8.5±11	NS: 18±8 WS: 19±8.5	NS: 16±7 WS: 18.5±8	-	NS: 14.5±4 WS:13.5±5	-
(Boyden et al., 2000)	% MVC	High-bar squat (P)	-	-	-	HIR 10º: 65%: 95.3±1.2 75%: 95.8±1.2 0º: 65%: 94.2±1.2 75%: 95.2±1.0 HER 10º: 65%: 93.8±1.0 75%: 96.2±1.0 HER 20º: 65%: 94.6±2.1 75%: 97.1±0.8	HIR 10º: 65%: 98.1±0.7 75%: 96.9±1.2 0º: 65%: 98.6±0.5. 75%: 97.7±0.7 HER 10º: 65%: 97.6±0.7. 75%: 97.9±0.8 HER 20º: 65%: 96.5±1.1 75%: 96.9±1.2	HIR 10º: 65%: 88.8±2 75%: 92.2±2 0º: 65%: 83.8±2 75%: 89.5±2 HER 10º: 65%: 89.0±3 75%: 93.2±1 HER 20º: 65%: 86.9±4 75%: 92.1±2	-	-	-	-	-
(Wright et al., 1999)	% MVC	High-bar squat (F)	-	-	-	-	-	-	43.5±13.3	45.9±13.7	-	-	-
(Blanpied, 1999)	% IMVC	Guided squat	-	-	-	IL: 20.3±12.5 FF: 21.1±13.1	IL: 12.5±5.6 FF: 26.6±9.9	IL: 24.5±8.8 FF: 30.5±9.3	-	-	-	-	-

(McCaw & Melrose, 1999)	Raw (µV*s)	Low-bar squat	60%RM: (NS): 5.2±2.8 (NW): 5.0±2.8 (WS): 5.3±3.9 75%RM: (NS): 5.9±3.5 (NW): 5.5±3.2 (WS): 6.9±3.8	-	60%RM: (NS): 6.1±1.9 (NW): 2.85±1.75 (WS): 2.7±1.9 75%RM (NS): 3.7±2.6 (NW): 3.7±2.3 (WS): 3.8±2.4	60%RM: (NS): 22.7±7.1 (NW): 22.1±6.6 (WS): 22.7±7.9 75%RM: (NS): 26.7±8.4 (NW): 27.1±8.9 (WS): 27.1±8.7	60% RM: (NS): 19.5±10.6 (NW): 19.2±9.9 (WS): 19.9±10.7 75% RM: (NS): 23.4±12.4 (NW): 22.7±12.4 (WS): 22.6±12.7	60% RM: (NS): 11.05±7.4 (NW): 10.6±7.0 (WS): 11.1±8.1 75% RM: (NS): 13.1±8.7 (NW): 13.2±8.5 (WS): 14.0±9.4	-	-	-	-	-

Values are expressed as Mean ± Standard Deviation or as a percentage. EMG: Electromyography; GM: Gluteus Maximus; GMed: Gluteus Medialis; HA: Hip Adductors; VL: Vastus Lateralis; VM: Vastus Medialis; RF: Rectus Femoris; BF: Biceps Femoris; ST: Semitendinosus; TA: Tibialis Anterior; GN: Gastrocnemius; SL: Soleus; %IMCV: percentage of an Isometric Maximum Voluntary Contraction; %MVC: percentage of the historic Maximum Voluntary Contraction; %RMS: percentage of peak Root Mean Square (RMS); µV: microvolts; F: full range of motion squat; P: squat to parallel; Q: quarter of a full ROM squat (partial squat); HIR/HER: Hip Internal/External Rotation; NW: Normal Width; X1.5: stance width at 1.5 times the normal stance; X2: stance width at 2 times the normal stance; NS: Narrow Stance; WS: Wide Stance; IL: feet in line with the body; FF: Feet placed Forward of the body line.

observed a slightly higher activation on the gluteus in the full-ROM squats in comparison to the other two modalities, other authors found no differences, or even higher gluteus activity values in the parallel squats (da Silva et al., 2017; Hammond et al., 2016). The effect of this technical modification was only assessed in the high-bar squat.

Stance width

This technical modification was included in the analysis of the high-bar (Escamilla et al., 2001; Paoli et al., 2009) and the low-bar (McCaw & Melrose, 1999) squat. The main effect of having a wider stance was a higher activation on the gluteus (McCaw & Melrose, 1999; Paoli et al., 2009). Variations on the stance width did not produce an effect on the activation of the quadriceps, hamstring, and gastrocnemius (Escamilla et al., 2001).

Hip rotation

Different hip rotations (i.e. orientation plane of the foot or knees) were only tested in high-bar squats. The main results of this technical modification were an increase in the activity of the hip adductors (Pereira et al., 2010). No significant effects of different hip rotations on the quadriceps were observed (Boyden et al., 2000).

Feet placement in line with the body or ahead

This technical modification was only tested in the guided squat, as this machine allows the subject to place the feet in line with the body or ahead. When the feet were placed in line with the body major activity on the quadriceps (i.e. normal activity pattern of a high-bar squat) was observed. In turn, when the feet were placed in front of the body line, higher activity was detected on the gluteus and hamstrings compared to the quadriceps (Blanpied, 1999).

Table 3. Quality assessment of the included studies.

Author (year)	1	2	3	4	5	6	Total
Bautista (2019)	+	+	+	+	+	+	6
Andersen (2019)	+	+	+	+	+	+	6
Delgado (2019)	+	+	+	+	+	+	6
Wu (2019)	+	+	+	+	+	+	6
Korak (2018)	+	+	+	+	+	+	6
Elliasen (2018)	+	+	+	+	+	+	6
McCurdy (2018)	+	+	+	+	+	+	6
Iversen (2017)	+	-	+	+	+	+	5
da Silva (2017)	+	+	+	+	+	+	6
Contreras (2016)	+	+	+	+	+	+	6
Hammond (2016)	+	+	+	+	+	+	6
Contreras (2015)	+	+	+	+	+	+	6
Yavuz (2015)	+	+	+	+	+	+	6
Aspe (2014)	+	+	+	+	+	+	6
Van den Tillar (2014)	+	-	+	+	+	+	5
Andersen (2014)	+	+	+	+	+	+	6
Gorsuch (2013)	+	+	+	+	+	+	6
Lynn (2012)	+	+	+	+	+	+	6
Robbins (2011)	+	+	+	+	+	+	6
Pereira (2010)	+	+	+	+	+	+	6
Fauth (2010)	+	+	+	+	+	+	6

Ebben (2009)	+	+	+	+	+	+	6
Schwanbeck (2009)	+	+	+	+	+	+	6
Gullett (2009)	+	+	+	+	+	+	6
Paoli (2009)	+	+	+	+	+	+	6
Caterisano (2002)	+	+	+	+	+	+	6
Escamilla (2001)	+	+	+	+	+	+	6
Boyden (2000)	+	+	+	+	+	+	6
Wright (1999)	+	+	+	+	+	+	6
Blanpied (1999)	+	+	+	+	+	+	6
McCaw (1999)	+	+	+	+	+	+	6

DISCUSSION

This study aimed to gather data on the muscular activation of the lower limb during five different variations of the squat exercise (i.e. high-bar squat, front squat, overhead squat, guided squat, and low-bar squat), looking forward to identifying the main muscle group involved and the variation with the higher activation levels. In the following lines, the main findings are going to be compared and discussed following the scientific body of knowledge.

In summary, almost all the studies found the major activity on the anterior thigh muscles, which are involved in the knee extension and are part of the quadriceps (vastus lateralis, vastus medialis, and rectus femoris), with the highest activation observed on the vastus lateralis. Only Andersen et al. (2014) and Gullet et al. (2009), reported higher activation levels on the hamstrings than on the quadriceps, in the front squat and high-bar squat, respectively. These uneven results may be due to the secondary function of the hamstrings as hip extensors (Netter, 1999). Also, the hamstrings (biceps femoris, semitendinosus, semimembranosus) are not actual antagonists in the squat exercise, but contract with the quadriceps in their function of stabilizing the tibia and the knee joint (Schoenfeld, 2010). However, hamstrings activation should be only moderate during the squat performance (Escamilla et al., 2001). Regarding the comparison between the gluteus and hamstrings, there is some controversy on which has a higher activation (see "*results: high-bar squat*" section, and Table 2). Attending to the squat biomechanics, the gluteus act as a powerful hip extensor and also as a knee and hip stabilizer. Gluteus activation mainly depends on the force arm length which is conditioned by different technique factors such as the depth, the stance width (McCaw & Melrose, 1999; Paoli et al., 2009; Schoenfeld, 2010). Concerning the calves, low activation levels have been observed in comparison to the thigh muscles. Attending to their main functions (Netter, 1999), these lower levels of activation may reside in the use of stable surfaces to perform the squat and the limited contribution of the ankle muscles in the squat movement.

As can be seen in the results, there are technical and electromyographical variations when the position of the bar changes (Pham et al., 2020). For instance, the load in the performance of a high-bar squat, a front squat, or an overhead squat, is shared between the knees and the hips (Comfort et al., 2018), with the main focus on the vastus lateralis and medialis as knee extensors (Aspe & Swinton, 2014; Contreras et al., 2015, 2016; Delgado et al., 2019; Ebben et al., 2009; Hammond et al., 2016). In turn, a higher hip involvement has been reported in the low-bar squat (Glassbrook et al., 2017, 2019; Wretenberg et al., 1996). In this variation, the trunk inclination is greater, and thus, gluteus and hip extensors activity is enhanced in comparison to other variations of the squat exercise. However, the low-bar squat stills a knee-extensors dominant exercise (McCaw & Melrose, 1999). Further research on the electromyographic activity of this squat variation is needed to better understand the neuromuscular processes involved.

Comparing the activation levels of each variation

Firstly, it is important to bear in mind that higher levels of muscle activation are enhanced in the squat exercise with increasing loads (Aspe & Swinton, 2014; Boyden et al., 2000; McCaw & Melrose, 1999; Paoli et al., 2009). The lever arm between the external load (i.e. the barbell) and the centre of mass of the body plays an important role in this regard (Gullett et al., 2009).

In the low-bar squat the lever arm is relatively shorter, and the position of the bar (below the acromion) is more biomechanical favourable than in the rest of the variations (Glassbrook et al., 2017, 2019; Wretenberg et al., 1996; see figure 2). Due to these abovementioned facts, the low-bar squat is the variation in which higher loads can be used, and thus, higher activation levels may be achieved. No significant differences were observed between the activation in a high-bar squat and a front squat (Gullett et al., 2009; Korak et al., 2018) and thus, both would be classified at the same level after the low-bar squat. These authors reported similar knee extension momentum, and comparable gluteus implication has been reported in both variations of the squat exercise (Neto et al., 2020). Concerning the overhead squat, lower muscle activity on the lower limb has been observed in comparison to the aforementioned variations. This is due to the greater involvement of the upper body to hold the bar and stabilize the spine during the execution (Aspe & Swinton, 2014; Bautista, 2019). Moreover, there are many factors such as the strength and shoulder mobility, which limit the load used in this exercise. Understanding that load increases entail increases in activation level (Aspe & Swinton, 2014; Boyden et al., 2000; McCaw & Melrose, 1999; Paoli et al., 2009), this squat variation would be positioned after the low-bar squat, the high-bar, and the front squat. Finally, Schwanbeck et al. (2009), Blanpied (1999), and Clark et al. (2012) in their revision of the literature pointed the guided squat as the variation provoking the lowest activation levels. One possible explanation for these results would be the nature of a guided exercise, eliminating most of the activity of the stabilizers.

Technical factors involved

Apart from the total load used, the depth has been shown to influence muscle activity patterns and the level of activation. In this line, lower activation levels were observed in partial squats (i.e. approximately 45º of knee movement) compared to the parallel or full range of motion squats (Gorsuch et al., 2013; Hammond et al., 2016). Similarly, Paoli et al. (2010) observed in their study that a reduction in the ROM decreased muscle activation levels on the shoulder when performing a military press. This finding relates to ours and strengthens the idea that a greater ROM entails a greater muscle activation. In terms of the influence of the ROM on the muscle activity pattern, no significant conclusions could be extracted from the analyses, with contrary findings among the reviewed articles (Caterisano et al., 2002; da Silva et al., 2017; Hammond et al., 2016; Neto et al., 2020). The stance width is another parameter that influences the muscle activity patterns in the squat. For instance, the hamstrings, gluteus maximus, and the hip adductor have all shown significantly greater activity in the wider stance squat compared with the narrow stance (Escamilla et al., 2001; McCaw & Melrose, 1999; Paoli et al., 2009). One of the main functions of the gluteus maximus is hip abduction (Netter, 1999) and thus, a wider stance facilitates this action of the gluteus. No other muscle activity was altered with varying stance widths (Escamilla et al., 2001). Finally, the rotation of the hips has been shown to increase the activation of the hip adductors (Pereira et al., 2010), with no significant changes in the activation patterns of the rest of the analysed muscles (Boyden et al., 2000).

Limitations

The included studies have some limitations that should be listed. In this regard, none of the studies indicate what type of isometric contraction (e.g. pushing or holding; Schaefer & Bittmann, 2017) performed the subjects to obtain the isometric maximum voluntary contraction to standardize the results. In this line, it is worth mentioning that standardization values are uneven, and this may entail a problem when trying to compare and discuss results. Also, one study found significant differences between the upper and lower fibres of the gluteus (Contreras et al., 2016). These differences between fibre bundles of the same muscle may condition the EMG results and thus, measurement procedures should be clearly stated in future studies. Finally, and even all the procedures of the present review were carefully carried out it is not free of limitations. The standardization made in the values by the authors may limit the analysis of each phase of the execution (i.e. eccentric and concentric). Future studies should review the literature comparing the activation in each phase. Also, the disparities between the included studies may carry to limited comparisons and extraction of conclusions. Finally, our inclusion criteria did not include variable resistance or different bar-types. These factors may provide the strength and conditioning professionals and athletes to further understanding of squat exercises.

CONCLUSION

This study highlights the importance of studying the neuromuscular acute effects of the squat to deeply understand the exercise and its variations and individualize resistance exercise programs. In brief, we observed that the squat, independently of the variation performed, is a knee-extensor dominant exercise. Different variations entailed different activation pattern, and activation levels. The low bar squat was the variation with higher activation levels due to the possibility of using a higher load. This movement has a considerable involvement of the hip muscles. High-bar squat and front squat provoked similar activation patterns due to having a similar lever arm. In this regard, the lever arm is greater in the overhead squat and thus, the activation levels are lesser (due to a limited capacity of using a high load). Finally, the guided squat was the variation with lower activation levels due to not require stabilization. The evidence presented in this study may help the strength and conditioning professionals and practitioners with the exercise selection depending on the muscular targets and the individual characteristics of the athlete.

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9.1.3 Article 3

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Research article

Adding the Load Just Above Sticking Point Using Elastic Bands Optimizes Squat Performance, Perceived Effort Rate, and Cardiovascular Responses

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Abstract

Modifying basal elongation of elastic bands (EB) has been proven useful to increase some parameters of the intensity in variable resistance training. Therefore, the question arises as to whether the pertinent resistance could be applied with EB immediately above the sticking point in squat exercises to optimize the performance. The purpose was to analyze some variables of the external (kilograms and number of repetitions) and internal load (heart rate, blood pressure, and rate of perceived exertion) after six different conditions of the squat exercise when using weight plates (WP) or EB (placed at different points of the range of motion) and applying maximal or submaximal effort. Twenty physically active males (25.50 ± 5.26 yrs) underwent two sessions for familiarization and one for assessment. The six conditions (three with WP and three with EB) were randomly performed. The sticking point of each subject was measured using the knee joint angle and the resistance was applied with EB at this height. Immediately after finishing each set subjects reported perceived effort rate and cardiovascular measurements were taken. Repetitions completed, and kilograms used were recorded. Repeated measures testing evaluated differences between conditions. EB permitted performing 8 more repetitions compared to WP when the same load was added at standing position. Adding the load immediately above the sticking point significantly ($p < 0.05$) increased 24.7% the kilograms used and permitted participants to perform 3 more repetitions. Internal load measurements suggested that EB could significantly ($p < 0.05$) reduce the perceived effort rate and/or physiological stress depending on their application. EB are a suitable device to load the bar for squat exercises in fit young men. According to the necessities of the subjects, if the load with EB is added at different points of the range of motion, it could be possible to overcome the sticking point, to maximize the performance and/or modulate cardiovascular and perceptual responses.

Key words: Weightlifting, resistance training, variable resistance, heart rate, blood pressure, physical exertion.

Introduction

Elastic Bands (EB) are increasing in popularity for strength training for both health and physical performance (Colado et al., 2010; 2020; Colado and Triplett, 2008; Saeterbakken et al., 2014; Soria-Gila et al., 2015). EB have been shown to induce similar neuromuscular activation and adaptations to free weights and machines (Colado and Triplett, 2008; Colado et al., 2010; Sundstrup et al., 2012; Iversen et al., 2017), and provide optimal muscle stimulation across the entire range of motion for different resistance exercises such as the squat (Andersen et al., 2015; Saeterbakken et al., 2016; Joy et al., 2016).

The kilograms provided by EB in squat exercises decrease with decreasing knee angles, due to the elongation coefficient and regardless of gravity (Saeterbakken et al., 2016; Andersen et al., 2016). Through this part of the range of motion, the length of the bands is shorter, and thus, they add fewer kilograms to the exercise. Conversely, there is an increase in the kilograms with increasing knee angles (i.e. when the length of the bands is longer). This property of the EB may affect the outcomes when comparing EB to constant resistance devices. In one research aimed at comparing constant and variable resistances in squats at 6 repetitions maximum (RM) load, EB did not provide enough resistance to achieve the desired kilograms (Saeterbakken et al., 2016). Therefore, the authors needed to use weight plates (WP) in combination with the variable resistance to achieve the appropriate load. In this sense, Iversen et al. (2017) in their review reported lower muscle activation levels during the parts of the range of motion where the bands were relatively slack. These authors highlighted the necessity of using EB with considerable tension to reduce the differences in external loading with WP.

Different strategies have been proposed such as increasing the number of bands and pre-stretching the band to increase the kilograms provided by the EB (Treiber et al., 1998; Aboodarda et al., 2013; Page et al., 2015). The pre-stretch consists of incrementing the initial tension of the band, either augmenting the distance from the handle to the attachment (Treiber et al., 1998; Page et al., 2015) or shortening the initial length of the band (Aboodarda et al., 2013). Through these uses of the EB, authors obtained similar or even higher muscle activation levels (Aboodarda et al., 2013), improvements in functional performance for sports (Treiber et al., 1998; Page et al., 2015) and further strength gains (Treiber et al., 1998) than with constant resistance. However, the aforementioned strategies do not take into account the variability between the subject's characteristics such as height or execution form. In this context, Iversen et al. (2017) specified the limited opportunity for manipulating the amount of pre-stretch in exercises such as the squat where the height of the person may be a limiting factor. Under the light of this fact, the necessity arises of finding a method that considers the individual's characteristics when looking forward to increasing the kilograms provided by the EB in squat exercises. This could be potentially useful to maximize the physical benefits derived

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from resistance exercises with variable resistance.

The squat is one of the most commonly used resistance exercises for performance and health due to its biomechanical and neuromuscular similarities to a wide range of athletic and everyday activities (Schoenfeld, 2010; Clark et al., 2012; Andersen et al., 2016; Kompf and Arandjelović, 2017). A squat program periodization is often measured or dosed by the external and internal load. Kilograms employed and the number of repetitions performed are some of the specific variables commonly used to quantify the external load, while different physiological and perceptual variables are used to quantify the internal load (Halson, 2014). For instance, the heart rate (HR), blood pressure (BP), and subjective scales of the rate of perceived exertion (RPE) are recognized as an adequate reflection of the physiological and physical performance responses, both with WP and EB (Robertson et al., 2003; Colado and Triplett, 2008; Colado et al., 2010; 2012; Halson, 2014; Maté-Muñoz et al., 2015), and are used to quantify the internal load (Halson, 2014; Iglesias-Soler et al., 2015). The most popular methods to determine training kilograms are repetitions maximum (RM) or percentage of 1RM (Reynolds et al., 2006; Bryanton et al., 2012; Aboodarda et al., 2013). Percentages of 1RM between 70 and 85% are commonly employed in resistance training programs (Kraemer et al., 2002; Schoenfeld, 2011).

The sticking region

During resistance training, when the load cannot be moved all the way upwards it is considered a failed repetition, and this often occurs in the so-called sticking region (Van den Tillaar et al., 2014; Saeterbakken et al., 2016; Andersen et al., 2016; Vigotsky et al., 2019). A sticking region has been repeatedly observed in the squat in numerous studies. Indeed, the phenomenon of the sticking region was first reported and studied in the squat (Kompf and Arandjelović, 2017). The sticking region is defined as the part of the range of motion in which a disproportionally large increase in difficulty occurs and is considered a mechanical constraint (Kompf and Arandjelović, 2016; 2017). This leads to a decrease in the upward velocity of the barbell (Van den Tillaar et al., 2014; Saeterbakken et al., 2016) and an increase in the chances of exercise form breakdown (Schoenfeld, 2010; Kompf and Arandjelović, 2016; Vigotsky et al., 2019). After this region, in the post sticking region velocity increases again due to more favorable biomechanical conditions (Van den Tillaar et al., 2014; Saeterbakken et al., 2016; Andersen et al., 2016). To locate where the sticking region finishes (sticking point) different biomechanical parameters are used such as the thigh angle relative to the ground (Kompf and Arandjelović, 2017), the knee flexion degrees (Escamilla et al., 2001), hip, knee, or even ankle joint degrees (Hales et al., 2009; Van den Tillaar et al., 2014), and so on. Focusing on the knee joint angle formed by the tibia and femur (standing position at 180º) (Figure 1), those aforementioned authors reported angles of 101.21º (Hales et al., 2009), 102º (Van den Tillaar et al., 2014) and 121º (Escamilla et al., 2001), the average being approximately 108º.

In order to overcome this biomechanical disadvantage, different techniques have been proposed such as forced repetitions, drop sets (Schoenfeld, 2011), accommodation, and use of variable resistance (EB or chains) (Kompf and Arandjelović, 2016). In particular, EB have been tested and identified as a suitable device due to providing lower loads during the more mechanical disadvantageous region of the range of motion (i.e. below the knee sticking point at lower knee angles) and greater loads with increasing knee angles (Kompf and Arandjelović, 2016; Joy et al., 2016; Andersen et al., 2016; Iversen et al., 2017). However, to the best of our knowledge, no previous research has attempted to equate the external load provided by the EB with that provided by the constant resistance in squat exercises. Bearing in mind the aforementioned strategy of incrementing the basal tension of the bands (Treiber et al., 1998; Aboodarda et al., 2013; Page et al., 2015), the question arises as to whether EB could be placed with the pertinent load immediately above the knee sticking point in a squat. This individual-based approach may create an overload in the more mechanically efficient parts of the range of motion, reducing the differences in intensity with the constant resistance and thus, maximizing the performance (Iversen et al., 2017).

Considering all the aforementioned previous research, the purpose of the present study was to analyze the physical performance (kilograms used and the number of repetitions completed), the perceived effort rate (RPE), and cardiovascular (HR and BP) responses to a squat exercise protocol on a Smith Machine when using WP or EB placed at different points of the range of motion (i.e. at standing position or immediately above the sticking point) and applying maximal and submaximal efforts. We hypothesized that depending on their application, EB will allow subjects to do a higher volume of repetitions with more kilograms in the standing position while presenting non-significant variations in the internal load.

Methods

Experimental approach to the problem

This descriptive, double-blinded study with a repeated-measures design analyzed the use of EB in six different conditions of the squat exercise on physically active healthy males. We measured the number of repetitions, and the kilograms (kg)) to quantify the external load (Halson, 2014). In addition, we analyzed RPE, systolic and diastolic blood pressure (SBP/ DBP), and HR as measurements of the internal load (Robertson et al., 2003; Colado et al., 2012; Halson, 2014; Maté-Muñoz et al., 2015; Iglesias-Soler et al., 2015; Iversen et al., 2017).

The six squat conditions were as follows: [1] 10RM (corresponding to approximately 75%1RM) with weight plates (WP) (10RMWP) loaded at standing position (i.e. body standing up straight in standard anatomical position); [2] 5RM with WP (5RMWP) loaded in the standing position, this load corresponded to approximately 85%1RM; [3] 9 submaximal repetitions with WP (9RSMWP) loaded in the standing position with the same kilograms as used for the 10RMWP condition; [4] 10 submaximal repetitions using EB (10REB) to load the bar with the same kilograms as used in the 10RMWP condition loaded in a standing position; [5] maximal number of repetitions using EB

(XRMEB) with the same kilograms as used for 10RMWP loaded in the standing position; [6] maximal number of repetitions with the same kilograms as used for 10RMWP but using EB to load the bar with the desired kilograms immediately above the estimated knee sticking point (i.e. 110º knee joint angle; fully extended knees at 180º) (Escamilla et al., 2001; Hales et al., 2009; Van den Tillaar et al., 2014; Kompf and Arandjelović, 2017) (XRMEBSP). The term weight plates (WP) was chosen over free weights due to the fixed nature of the Smith machine.

Participants

All measurements were carried out at the Optometric Clinic "Fundació Lluís Alcanyís" at the University of Valencia (Spain). We conducted the study in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki), and permission was provided by the University of Valencia's Ethics Committee on Human Research (H1499867368458). All participants voluntarily agreed to participate and were free to withdraw from the study at any time. Each participant was informed of the benefits, and risks of injury derived from the investigation before signing an institutionally approved informed consent form.

A sample size of 19 participants was determined by a power analysis (G*Power 3.0; Faul et al., 2007) assuming an α of 0.05, a power level of 0.8, an effect size of f(V) = 0.87, and a non-sphericity correction of ε = 1. Prior to the study, all subjects received a full physical examination to assess their posture and squat technique and confirm their validity for the study. Inclusion criteria were: 1) younger than 40 years old, 2) experience on strength training for at least 6 months and performing at least 2 days per week of lower limb training including squats, and 3) no musculoskeletal health issues. As a result, of the 30 recruited subjects, only 20 met the criteria and voluntarily participated in this study. All subjects were physically active males (25.50 ± 5.26 years old, 95% confidence interval (CI) [23.04-27.96]; body mass index 24.09 ± 2.06 kg/m2, 95% CI [23.13-25.05]; body fat 10.16 ± 2.23 %, 95% CI [9.12-11.20]; Squat 1RM 127.10 ± 24.10 kg, 95% CI [115.82-138.38]; ratio 1RM- bodyweight (relative strength) 1.70 ± 0.36, 95% CI [1.55-1.85]). All participants were instructed to avoid alcohol consumption and strenuous exercise 24h before any of the sessions. They were asked to consume their typical diet, drink 1L of water, sleep for at least 8h, and not consume stimulants, supplements, or smoke before the trial. Also, water intake was controlled throughout the entire trial, allowing subjects to drink at libitum to maintain proper hydration and performance (Kenefick, 2018).

Procedures

The exercise protocol consisted of three sessions: two for familiarization and assessment, and one for the experimental trial. All data were collected in a thermoneutral environment (~ 22ºC and ~ 60% humidity), and at the same time of day to avoid diurnal variations on subjects' performance (Sundstrup et al., 2012). All measurements were taken by the same researchers and were always conducted in the same laboratory. The physiological measurements were carried out in an adjacent space separated from the Smith machine by a partition screen to blind the researcher. As for the subjects, they were instructed to not look at the Smith machine before performing each condition. Participants rested in the aforementioned separated space while listening to music with headphones to avoid getting audible information about the next condition. Constant feedback was given, and two trained spotters were standing on both sides of the bar to ensure proper execution and to encourage maximum effort.

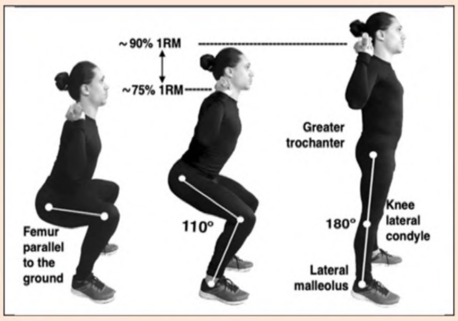

Figure 1. Relevant points of the squat performance in Condition 6. Lowest position (left), the position immediately above the estimated sticking point (middle) and standing position (right) are pictured. Anatomical points used to measure the knee angle are identified. Significant differences ($p < 0.001$; ES (d) = 1.15) on the relative load (percentages of one repetition maximum (1RM)) when adding the load immediately above the sticking point with elastic bands (Condition 6) are shown. Both 1RM percentages are rounded values, with ~75%1RM being 95.95 ± 17.88 kg [87.58-104.32], and ~90%1RM being 119.65 ± 22.86 kg [108.95-130.35].

In the first session, the participants signed the consent form, filled in the demographic questionnaire and the guarantee of data confidentiality, and underwent a physical examination. Height (m), weight (kg), and body fat percentage were obtained with a height rod and a bioelectrical impedance scale Body Composition Analyzer BF-350 (Tanita, Arlington Heights, IL). Body mass index (BMI) was calculated as weight/(height)2. Thereafter and before the warm-up, measurements of the pertinent knee angle were taken (Figure 1) and a mark was made on the Smith machine to identify the height of the bar when the subject was at this point of the range of motion. At this point, participants were instructed on how to perform the squats at the correct pace and how to use the OMNI-RES scales of perceived exertion with WP (Robertson et al., 2003) and EB (Colado et al., 2012). For further details on how to apply the RPE scales previous studies can be consulted (Maté-Muñoz et al., 2015; Naclerio and Larumbe-Zabala, 2017). The standardized warm-up included joint mobility, bodyweight exercises, jogging, and dynamic stretching. After the warm-up and before the RM testing, participants performed three sets of squats at the Smith machine: first, twenty repetitions without additional weight, and then two more sets of 15 and 12 submaximal repetitions; loads for the last two sets were selected according to participant's perceived 20RM and 15RM. Finally, maximum loads were assessed through a fatigue test with submaximal loads as previously reported in the literature (Reynolds et al., 2006). Subjects performed between 8 and 12 maximum repetitions. If a participant performed a number of repetitions that fell outside of the aforementioned range, another set with altered load was performed allowing at least a five-minutes rest; more time was permitted depending on the perception of the subjects (Laurent et al., 2011). Data were registered and used to obtain the load for 1RM using O'Connor or Brzycki formulas (Reynolds et al., 2006). Percentages were calculated for 75%1RM and 85%1RM.

A second session was used to ensure the validity of the maximum loads, the knee angle measurements, and the 75 and 85%1RM obtained during the first session, while participants gained further experience in using RPE scales. Subjects performed maximal and submaximal sets in random (https://www.random.org/lists/) order with different loads using EB and WP. If the subject was able to perform more than 10 repetitions with WP at 75%1RM or more than 5 repetitions at 85%1RM, weights were adjusted to mark the requirements.

The third session was targeted to evaluate all dependent variables. Firstly, participants underwent a physical examination to determine resting values for each physiological variable. After the warm-up, each of the six conditions was performed at random (https://www.random.org/lists/) and balanced order. For Condition 6, the bar was placed at the pertinent height and as many bands as needed to achieve the 10RM load were added. Thereafter, the bar was placed at the subject's standing position by a researcher, and afterward, the subject performed the set. All dependent variables were measured immediately after performing each condition in the following order: RPE, HR, and BP (SBP and DBP); the number of repetitions performed, and the kilograms were also recorded at that time if the condition required it. At least a five-minute rest was given between sets, more time was permitted depending on the perception of the subjects (Laurent et al., 2011).

Squat exercise

A high-bar back squat (bar placed across the shoulder on the trapezius, slightly above the posterior aspect of the deltoids) (Schoenfeld, 2010; Vigotsky et al., 2019) to a parallel depth (Clark et al., 2012; Bryanton et al., 2012; Saeterbakken et al., 2016) was performed. The stance width was established for each subject between the hips and shoulder (Schoenfeld, 2010). Shoes were used but no weightlifting belts or knee wraps were permitted (Clark et al., 2012; Vigotsky et al., 2019).

To standardize the range of motion, the sticking point, and pace of movement, a goniometer, tactile markers, and a metronome were used. The depth was adjusted with a horizontal elastic band when the femur (marked by the line from the great trochanter to the knee lateral condyle) of each subject was parallel to the ground. The participants had to touch the band (midthigh) in every repetition before starting the concentric phase. Moreover, a crossline auto-laser level was fixated with a tripod (Black and Decker LZR6TP, New Britain, CT) and was used as visual feedback for researchers in connection with the requested joint positioning during exercise. The tempo consisted in an inhalation-coordinated eccentric phase lasting two seconds (Schoenfeld, 2010) with a pause of one second at the lowest point (femur parallel to the ground), and an exhalation-coordinated maximum speed concentric phase (4 seconds for a complete squat). The pause at the transition from the eccentric to the concentric phase was designed to dissipate stored elastic energy within the muscles (Aboodarda et al., 2013).

Blood pressure and heart rate

Cardiac measurements were performed immediately after finishing each condition using a digital automatic blood pressure monitor (M6W HEM-7213-E (V), Omron, Japan). The intraclass reliability (α) of the instrument was excellent (Fleiss, 1986), being 0.90 for the SBP, 0.86 for the DBP, and 0.91 for the HR.

Rating of Perceived Exertion (RPE)

RPE for the overall body was measured immediately after finishing each of the six conditions with the OMNI-RES for weight training (Robertson et al., 2003) and the OMNI-Resistance Exercise Scale of Perceived Exertion for EB (Colado et al., 2012). These scales measure the perceived effort of the overall body (not the active muscles) in a 0-10 scale, being 0 "no effort" and 10 "maximum effort". The intraclass correlation coefficient of the RPE values given by the subjects when performing at 75 and 85%1RM in the familiarization and experimental sessions was 0.83, which is considered an excellent value (Fleiss, 1986).

Strength training equipment

A Multipower Smith Machine Powerline PSM144X (Body-Solid, USA) was loaded with 28mm cast iron plates (Domyos, France) ranging from 0.50 to 20 kg or with looped CLX elastic bands (TheraBand®, Akron, OH, USA). The barbell weighed 20 kg. To measure the load for each condition, a 100 g precision scale model 9179 SV3R (Salter, United Kingdom) was used.

Statistical analyses

Statistical analyses were performed using commercial Software IBM SPSS Statistics for Macintosh (Version 26.0; IBM Corp., Armonk, NY). A repeated-measures design was used to determine systemic variables fluctuations according to perceptual and physical performance variables after the squat exercise protocol. Normality of data distribution was evaluated using the Shapiro-Wilk test, showing a normal Gaussian distribution ($p > 0.05$) except for the RPE ($p < 0.05$). To assess differences between conditions in normally distributed variables, a one-way ANOVA for repeated measurements was used. Where Mauchly's sphericity assumptions were violated, Greenhouse-Geisser adjustment of the p-values was reported. Effect size (ES) was evaluated with eta partial squared (ηp^2), where $0.01 < \eta p^2 < 0.06$ constitutes a small effect, $0.06 \leq \eta p^2 \leq 0.14$ constitutes a medium effect, and $\eta p^2 > 0.14$ constitutes a large effect. When differences were detected, post-hoc tests with Bonferroni corrections examined where differences occurred. The magnitude of the paired differences was assessed through Cohen's effect size (ES). The results (Cohen's d coefficient) were interpreted following the specific scale to training research with negligible

(<0.2), small (0.2–0.5), moderate (0.5–0.8), and large (≥0.8) (Cohen, 1988). Non-parametric Friedman tests identified differences in RPE between conditions, and when differences were found, paired Wilcoxon signed ranks test showed where differences happened. Test-retest reliability of the instruments (blood pressure monitor and RPE scales) was assessed in a subsample of 10 subjects calculating the intraclass correlation coefficient (ICC). ICC was interpreted as poor (ICC < 0.40), moderate (0.40 ≤ ICC < 0.60), good (0.60 ≤ ICC < 0.80) or excellent (ICC ≥ 0.80) (Fleiss, 1986). An α of 0.05 was used to determine significance in all cases. All results are reported as mean and standard deviation (SD) with confidence intervals at 95%.

Results

External load

Repeated measurements testing revealed significant differences in the KG used, number of repetitions performed and reported RPE between the six conditions (KG: $F(5, 95) = 128.82$, $p < 0.001$, $\eta p^2 = 0.87$; number of repetitions: $F(5, 95) = 72.40$, $p < 0.001$, $\eta p^2 = 0.79$; RPE: $X2(5) = 64.17$, $p < 0.001$). Table 1 shows the performance variables and RPE outcomes for each of the six squatting conditions.

Adding the load for 10RM with EB immediately above the sticking point (Condition 6) resulted in a statistically significant increase of 24.7% ($p < 0.001$; ES (d) = 1.15) in the kilograms at standing position (+23.70 ± 9.45kg, 95% CI [19.27-28.12]) surpassing the theoretical 90%1RM of the participants (Figure 1). This load was also significantly higher than the 5RM load (+11.05 ± 9.02kg, 95% CI [6.83-15.27]; $p < 0.001$; ES (d) = 0.51).

While participants used significantly more kilograms, they were able to perform on average 3.45 ± 3.84 more repetitions (95% CI [1.65-5.25]) in the aforementioned Condition 6 than in Condition 1 (10RM with WP) ($p = 0.001$; ES (d) = 1.27), and 8.45 ± 3.85 more repetitions (95% CI [6.65-10.24]) than in Condition 2 (5RM with WP) ($p < 0.001$; ES (d) = 3.10). Concerning the comparison between the maximal effort at a 10RM load in the standing position with EB (Condition 5) and the 10RM with WP (Condition 1), participants performed on average 8.40 ± 4.86 more repetitions in the condition with EB (95% CI [6.13-10.67]) ($p < 0.001$; ES (d) = 2.44).

Internal load

Concerning the RPE, non-significant differences on RPE were observed between performing 10RM with WP (Condition 1) and performing about 18RM with EB (Condition 5) ($p > 0.05$). The lowest values were found in the condition comprising a submaximal effort of 10 repetitions at 10RM load with EB (Condition 4), with significant differences to the rest of the conditions (Condition 1: $p < 0.001$; ES (d) = 1.91; Condition 2: $p = 0.001$; ES (d) = 1.23; Condition 3: $p < 0.05$; ES (d) = 0.94; Condition 5: $p < 0.001$; ES (d) = 1.96; Condition 6: $p < 0.001$; ES (d) = 2.71). The condition consisting of a maximal effort with EB with 10RM load added immediately above the sticking point (Condition 6) resulted on the highest RPE, also with significant differences to the rest of the conditions (Condition 1: $p < 0.05$; ES (d) = 0.75; Condition 2: $p < 0.001$; ES (d) = 2.11; Condition 3: $p < 0.001$; ES (d) = 1.93; Condition 5: $p < 0.05$; ES (d) = 0.59).

Repeated measures testing indicated a significant BP and HR increase after each condition compared with baseline values; except for the DBP after the Condition 4 ($p = 0.075$) and 5 ($p = 0.085$). However, post-hoc analyses showed no significant differences between the six conditions on SBP or DBP. Regarding the HR, Condition 6 did not show significant differences with almost the rest of the conditions. The smallest increases were observed after a maximal effort of 5RM with WP (Condition 2: +28.00 bpm, 95%CI [18.04-37.95]), showing significant differences with the rest of the conditions. On the other hand, a maximal effort of about 18 repetitions using EB at 10RM load added at standing position (Condition 5) resulted in the highest HR, showing significant differences with all WP conditions and only a trend when compared with Condition 1 (Condition 1: $p = 0.05$; ES (d) = 0.29 ; Condition 2: $p < 0.001$; ES (d) = 0.92; Condition 3: $p < 0.05$; ES (d) = 0.35), and with the submaximal 10R with EB (Condition 4: $p < 0.01$; ES (d) = 0.53). Table 2 shows the cardiovascular variables outcomes after each condition and repeated measures testing concerning resting values; differences between conditions are also identified.

Table 1. External load variables outcomes and rate of perceived exertion of the different squatting conditions.

Condition	Kg at standing position	Number of Repetitions	RPE
1 (10RMWP)	95.95 ± 17.88 [87.58-104.32]	10.00	8.55 ± 0.88 [2,3,4,6] [8.14-8.96]
2 (5RMWP)	108.60 ± 20.24* [99.13-118.07]	5.00*	7.75 ± 0.72 [1,4,5,6] [7.41-8.09]
3 (9RSMWP)	95.95 ± 17.88 [87.58-104.32]	9.00	7.55 ± 0.99 [1,4,5,6] [7.09-8.01]
4 (10REB)	95.95 ± 17.88 [87.58-104.32]	10.00	6.50 ± 1.24 * [5.92-7.08]
5 (XRMEB)	95.95 ± 17.88 [87.58-104.32]	18.40 ± 4.86* [16.13-20.67]	8.65 ± 0.93 [2,3,4,6] [8.21-9.09]
6 (XRMEBSP)	119.65 ± 22.86* [108.95-130.35]	13.45 ± 3.84 * [11.65-15.5]	9.10 ± 0.55 * [8.84-9.36]

Note: 95.95 kg, 108.60 kg, and 119.65 kg corresponded to approximately 75%, 85% and 94% of participants' 1RM, respectively. A 20 kg barbell was used in all the conditions. *: Statistically significant difference compared to the rest of the conditions. [1, 2, 3, 4, 5, 6]: Significant difference with the condition 1, 2, 3, 4, 5, or 6. Values are expressed as mean ± standard deviation (SD) [95% Confidence Interval]. RPE: rate of perceived exertion; RMWP: repetition maximum with weight plates; RSMWP: submaximal repetitions with weight plates and with the same weight used for the 10RMWP condition; EB: elastic bands; REB: submaximal repetitions with EB with the same weight used for the 10RMWP condition; XRMEB: Repetitions to failure with elastic bands with the same weight used for the 10RMWP condition; XRMEBSP: repetitions to failure with EB and loaded with the same weight used for the 10RMWP condition and placed immediately above the knee sticking point.

Table 2. Internal load outcomes of the different squatting conditions.

Condition	SBP (mmHg)	DBP (mmHg)	HR (bpm)
Resting	126.65 ± 10.65* [122.30-131.05]	68.30 ± 6.08 [1,2,3,6] [65.65-70.90]	64.05 ± 10.98* [58.91-69.19]
1 (10RMWP)	148.05 ± 20.39 [139.45-157.85]	74.25 ± 8.72 [70.35-78.10]	105.45 ± 16.35 [2,4] [97.80-113.10]
Δ%	+16.90	+8.71	+64.64
Cohen's d	1.32	0.79	2.97
2 (5RMWP)	144.00 ± 16.089 [136.95-151.35]	73.55 ± 8.79 [69.85-77.45]	92.05 ± 18.48 * [83.40-100.70]
Δ%	+13.70	+7.69	+43.72
Cohen's d	1.27	0.69	1.84
3 (9RSMWP)	146.25 ± 23.33 [137.00-156.25]	74.00 ± 7.89 [70.60-77.30]	104.20 ± 17.40 [2,5] [96.06-112.34]
Δ%	+15.48	+8.35	+62.69
Cohen's d	1.08	0.81	2.76
4 (10REB)	146.40 ± 13.39 [140.45-152.05]	72.70 ± 9.17 [68.85-76.80]	100.60 ± 16.44 [1,2,5] [92.91-108.29]
Δ%	+15.59	+6.44	+57.06
Cohen's d	1.63	0.57	2.61
5 (XRMEB)	144.55 ± 18.40 [136.95-152.75]	72.35 ± 10.06 [68.10-76.90]	111.35 ± 23.25 [1,2,3,4] [100.47-122.23]
Δ%	+14.13	+5.93	+73.85
Cohen's d	1.19	0.49	2.60
6 (XRMEBSP)	146.45 ± 19.60 [137.90-154.50]	75.35 ± 10.63 [70.60-80.05]	107.85 ± 14.63 [2] [101.00-114.70]
Δ%	+15.63	+10.32	+68.38
Cohen's d	1.26	0.81	3.39

Note: Repeated measures testing in respect to resting values are displayed. *: Statistically significant difference compared to all other conditions. [1, 2, 3, 4, 5, 6]: Significant difference compared to conditions 1, 2, 3, 4, 5, or 6. Values are expressed as mean ± standard deviation (SD) [95% Confidence Interval]. Being SBP: systolic blood pressure; DBP: diastolic blood pressure; HR: heart rate; RMWP: repetition maximum with weight plates; RSMWP: submaximal repetitions with weight plates and with the same load used for the 10RMWP condition; EB: elastic bands; REB: submaximal repetitions with EB and the same kilograms used for the 10RMWP condition; XRMEB: Repetitions to failure with elastic bands with the same kilograms used for the 10RMWP condition; XRMEBSP: repetitions to failure with EB and the same kilograms used for 10RMWP condition and placed immediately above the knee sticking point; Δ%: percentage of variation.

Discussion

This study compared the physical performance, the perceived effort rate, and cardiovascular responses to a squat protocol using different training devices (EB or WP), and with different reference points to charge the total load when EB were used (i.e. initial position of the movement versus immediately above the sticking point). To the best of our knowledge, this is the first study that analyzes the performance in a squat movement with the load added immediately above the sticking point with elastic bands and thus may have important implications for exercise prescription.

Consistent with the hypothesis, the main finding was that compared with the 10RM with WP (Condition 1), adding the load for 10RM with EB immediately above the sticking point (Condition 6) permitted participants performing about 3 more repetitions with more kilograms (25% more kilograms at standing position; see Table 1) during at least 70 degrees of knee movement (from 110º to 180º at fully extended knees; see Figure 1). This condition also permitted participants to perform about 8 more repetitions with 10% more kilograms at the standing position than in 5RM with WP (Condition 2; see Table 1). Furthermore, physiological measurements of the internal load (BP and HR) were not significantly higher than almost the rest of the conditions (see Table 2) even though participants perceived Condition 6 as the hardest. These findings highlight the usefulness of this new method of applying the elastic resistance in squats for achieving more repetitions while using more kilograms and provoking similar physiological responses. Loading the elastic resistance immediately above the squat sticking point compared to adding the load in the standing position could induce higher muscle fiber recruitment due to using more kilograms over more repetitions, which may lead to better chronic adaptations (Soria-Gila et al., 2015). Supporting this fact, increments in load for the same squat variation have been shown to produce a positive impact on muscle activation (Clark et al., 2012), and developing muscle strength has been closely related to greater force application, longer duration of muscle tension and a greater total amount of work (Schoenfeld, 2011; Bryanton et al., 2012; Aboodarda et al., 2013).

Concerning the maximal effort with EB adding the load for 10RM at standing position (Condition 5), participants performed about 8 more repetitions until exhaustion than in 10RM with WP (Condition 1). This Condition 5 was not perceived as more exhausting and did not show BP differences with the aforementioned 10RM with WP. However, Condition 5 provoked a slightly higher HR compared with Condition 1 with a small effect size (Cohen's d) of 0.29. This fact confirms that in comparison with WP, adding the same load at the standing position with EB allows for a larger time under tension while maintaining similar internal load values. A larger time under tension has been shown to increase glycolysis metabolism and may promote greater muscle adaptations by stimulating delayed muscle protein synthesis at 24-30h of recovery (Burd et al., 2012).

In reference to the submaximal conditions, EB provoked comparable internal load outcomes when kilograms at standing position and volume of repetitions are similar to the condition with WP (Conditions 3 and 4 respectively;

see Table 2). Conversely, 10 repetitions with the load for 10RM added at the standing position with EB (Condition 4) was perceived as the least demanding condition (see Table 1). This fact is probably due to having the minimum total amount of work. The similarities in the cardiovascular outcomes may be associated with the comparable number of repetitions as explained further below (see "internal load" section).

A general approach to the use of EB in squats

Bearing in mind the central target of this research, it is worth discussing the potential use of EB as a device to load the bar in squats. Within a parallel squat, muscle activation is greatest in the last phase of the descent and the first phase of the ascent (Clark et al., 2012). Knee extensors' effort increases with an increment on the squat depth, and a higher activity on hip extensors and ankle plantar flexors occurs when the barbell load increases (Bryanton et al., 2012). Since EB provide fewer kilograms in the lower part of the range of movement, and more in the upper part (Andersen et al., 2016), EB could optimally activate the neuromuscular system through the entire range of motion (Saeterbakken et al., 2014), moreover adding the load immediately above the sticking point. From a practical perspective, squatting with EB could allow the athlete to go down to the deepest point of the range of motion with less mechanical stress acting against the knees on the sticking region (Schoenfeld, 2010; Kompf and Arandjelović, 2016; Vigotsky et al., 2019). And then, immediately after this mechanical disadvantageous range of motion muscles of the hip and ankles would be enhanced with the increment in the load due to the elongation coefficient of the EB (Bryanton et al., 2012; Saeterbakken et al., 2016; Kompf and Arandjelović, 2017). Combining all these facts from a biomechanical point of view suggests that in similar conditions of load EB are an appropriate device to load the bar in squats with no need to use WP.

Nevertheless, most of the previous research has used EB with a lower tensile force or in combination with higher loads of constant resistance devices (Saeterbakken et al., 2014, 2016; Andersen et al., 2015; Iversen et al., 2017). Only some studies are in line with our procedures and have used EB to achieve similar or even higher external resistance than the one used with constant resistance devices (Colado and Triplett, 2008; Colado et al., 2010; Andersen et al., 2016; Aboodarda et al., 2013). It is important to note that in our study the weight of the barbell could be considered as constant resistance. It represented about 20% of the total load in Conditions 4 and 5, and less than 17% in Condition 6 (Table 1). Our findings support the use of EB to achieve similar or even higher loads than constant resistance devices, moreover with the new strategy of adding the load above the sticking point. However, our results should be interpreted cautiously and be compared with the existing literature.

Applying the pertinent load after the mechanical disadvantage

As far as we are aware, this is the first study that describes the acute effects of applying the load with EB in two different points of the range of motion in a squat (i.e. on the initial position of the exercise versus immediately above the sticking point). Therefore, our findings in respect of the increments in the external load when adding the elastic resistance immediately above the sticking point are difficult to compare with the existing literature. Only a few authors have similarly used EB (Treiber et al., 1998; Aboodarda et al., 2013; Page et al., 2015). For instance, Page et al. (2015) used EB initially elongated 15cm beyond their original length to perform different upper body and trunk exercises. It resulted in greater improvements in the serve of racquetball players than their usual training program. Similarly, Aboodarda et al. (2013) shortened the EB by 30% of its resting length to perform 8RM of a biceps curl on anatomical position and identified higher muscle activation levels than non-shortened EB or dumbbells at the end of the concentric phase and beginning of the eccentric phase. Results of Aboodarda et al. (2013) showed how the reduction of the basal length of the EB at the beginning of the movement is another way to increase the load above the sticking point. As happened in our study, this specific strategy allows for an increase in the kilograms moved among the less mechanically effective region of the movement, and thus an increase in muscle activation in comparison to the habitual use of the EB (Behm and Colado, 2012; 2013; Clark et al., 2012; Aboodarda et al., 2013). It also reduces differences in muscle activation compared to constant resistance in this region of the range of motion (Aboodarda et al., 2013). This strategy leads to an increase in muscle activation levels due to the possibility of using more kilograms throughout the more mechanically effective region of the movement, both in the concentric and eccentric phases (Kompf and Arandjelović, 2016, 2017; Saeterbakken et al., 2016) as has been shown in our study. It is also important to note that while we found that five less repetitions were performed between adding the load immediately above the sticking point or at standing position (Conditions 6 and 5 respectively; see Table 1), Aboodarda et al. (2013) found no difference on the number of repetitions between performing with shortened or non-shortened EB. This fact may be due to the difference in loads between both methods. They only encountered significant differences in the load at the first degrees of the concentric phase and the final segments of the eccentric phase of the biceps curl (i.e. first degrees of elbow flexion in anatomical position). In contrast, we found significantly higher loads in the last phase of the concentric and at the start of the eccentric phase of the squat exercise. These differences could be explained through the approach to the use of the EB. Our procedures are not based on elongating or shortening the EB depending on its basal length but adding the elastic resistance at different heights to overcome the sticking region depending on the athlete's biomechanics. In this regard, 110º of knee joint angle (i.e. 70º of knee flexion or a tight angle relative to the ground of 20º) seems to be a good point to add the load with the elastic bands.

From an applied point of view, our study is in agreement with other previous research regarding the possibility of lifting more kilograms when EB are added to the traditional training with WP. Joy et al. (2016) obtained positive increases in force production when implementing EB in combination with traditional constant resistance during exercises performed with concentric movements as fast as possible. These chronic positive neuromuscular adaptations were probably instigated by performing with more kilograms with the EB, overcoming the sticking point in each set of the resistance training program (Soria-Gila et al., 2015; Kompf and Arandjelović, 2016, 2017). According to our results in terms of squatting exclusively using EB, we can state that participants can load 25% more kilograms at standing position (Condition 6) than the kilograms used for a 10RM set with traditional weight plates performed at a controlled pace of movement (Condition 1; see Table 1). This could mean that it is possible to directly and easily add 25% more kilograms at the standing position with no need to measure the sticking point before beginning the exercise to add the pertinent weight. It can also be pointed out that it may be possible to add the extra kilograms with EB to the traditional WP load to obtain these benefits during a 10RM set performed with a controlled pace of movement as previously suggested in the literature (Joy et al., 2016). However, this condition has not been analyzed by us, and the final number of repetitions performed may vary.

Internal load outcomes

Our results in cardiovascular terms are in accordance with those published on HR and BP increments after high-intensity squat exercise, with greater increases after the sets with a higher number of repetitions (Iglesias-Soler et al., 2015). Cardiovascular responses seemed to be influenced by the volume rather than by the kilograms or material used.

Regarding the RPE (see Table 1), EB conditions were perceived as less demanding than WP conditions when performing at similar loads (Conditions 3 and 4). Furthermore, performing about 18RM with EB was not perceived as more demanding than performing 10RM with WP (Conditions 1 and 5 respectively). One possible explanation for the Condition 6 (load added immediately above the sticking point) being perceived by the participants as the most demanding condition could be the higher amount of total work (higher volume of repetitions performed with more kilograms). In accordance with our results (see Table 1), Sundstrup et al. (2012) reported a lower RPE after 3RM of lateral raises with EB (4.54 ± 2.09) than after repetitions to failure at approximately 15RM load also with EB (7.58 ± 2.02). Our findings are in contrast with some studies which did not find significant differences between performing at similar effort levels with elastic or constant resistance (Iversen et al., 2017). These differences may be due to using the RPE scales for the active muscles or, in contrast, for the overall body (Colado et al., 2012).

Limitations and future directions

Even though all the procedures were carefully supervised, and all statistical parameters were accurately and positively tested during the collection of data, some specific issues should be listed as potential sources of bias.

First of all, the variability between exercise protocols makes it difficult to compare results with the available literature, which limits the generalization of our findings. Regarding the load, obtained 5RM and 10RM (Table 1) are consistent with the percentages (Reynolds et al., 2006; Andersen et al., 2015) and kilograms (Joy et al., 2016) used by some studies with a varied subject population. On the other hand, some researches assessing free barbell squat reported lower average loads (Bryanton et al., 2012; Saeterbakken et al., 2016; Andersen et al., 2016; Iversen et al., 2017), and one study showed greater loads (Vigotsky et al., 2019). These differences could be explained through the variability in the sample characteristics, and the disparities of performing the squat in a Smith Machine or with a free barbell. In this respect, an increment of 14 to 23 kg has been reported when using Smith Machine due to the more stable conditions (Behm and Colado, 2012, 2013; Clark et al., 2012). Although we used a Smith Machine looking forward to ensuring equal conditions amongst all of the subjects, the study should be replicated using a free barbell. Also, this new procedure of using the sticking point to add the pertinent load could be used in different resistance exercises which have a measured sticking point such as the deadlift and the bench press. Besides, it is worth mentioning that our sample consisted only of males.

Secondly, it could be interesting to evaluate the kilograms used throughout all of the range of motion looking forward to comparing the mean external resistance between the elastic bands and the weight plates. In this regard, in different pilot studies we performed, we found a descent in the load of about 15% from the sticking point to the lowest point of the execution (in our pilot studies located at 81.12 ± 3.74 knee joint angle degrees).

Finally, as it was stated before, in the absence of more specific scientific evidence obtained with medium and long-term intervention studies, our comments are momentarily basic suggestions as to whether adaptation to applying the total weight with EB immediately above the sticking point conditions could chronically result in even higher levels of central neural activation, muscle hypertrophy, and increased strength development. All the procedures in this study were focused on identifying acute variations in the training load, and thus it would be interesting to introduce the use of the loading immediately above the sticking point with EB in a short or long-term strength periodization program to check for chronic adaptations. Also, and even though we did not analyze this condition, our results suggest that 25% more of the pertinent load could be directly added with elastic bands at the standing position with no need to measure the sticking point. While caution must be applied until more scientific evidence arrives, the strategies presented may allow the trainer or the athlete to select, according to their necessities, the optimal point of loading the resistance to maximize their physical performance and/or cardiovascular and perceptual responses.

Conclusion

The combination of findings presented provides a new approach to the use of elastic bands for strength training exercises. In summary, our findings showed that depending on how the bands are applied (i.e. immediately above the sticking point or at the standing position), squatting with

EB: 1) allows the participants to move more kilograms after the sticking region than squatting only with WP, 2) facilitates a higher number of repetitions, which could permit a greater time of muscle activity or time under tension (i.e. how long a muscle is under strain during a set), and 3) optimizes cardiovascular responses and perceived effort rating.

Bearing in mind these abovementioned facts, the evidence presented in this study highlights the possible practical applications of EB for subjects who need to exercise with high loads. Additionally, those subjects who want to avoid high cardiovascular and perceptual stress during strength training, without reducing muscular demands could also safely use EB in different ways. In conclusion, elastic bands could reduce cardiovascular and perceptual stress depending on each type of application and are presented as a solid option to perform resistance training at high loads and volumes with no need to combine them with weight plates.

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Key points

- This paper presents a new strategy of applying the elastic bands for resistance exercises (i.e. immediately above the sticking point).
- Adding the load immediately above the sticking point with elastic bands allow to achieve more repetitions and use more weight than weight plates do.
- Blood pressure and heart rate responses are similar to a 10RM with weight plates or an 18.40RM with elastic bands.
- When both elastic bands and weight plates are equated in weight (at standing position), volume and level of effort (submaximal), elastic bands are perceived by the subjects as less demanding.

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9.1.4 Article 4

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Effects of squatting with elastic bands or conventional resistance-training equipment at different effort levels in post-exercise intraocular pressure of healthy men

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ABSTRACT: This study aimed to compare intraocular pressure (IOP), mean ocular perfusion pressure (MOPP) and central corneal thickness (CCT) acute adaptations to squat exercise using elastic bands (EB) or weight plates (WP) together with the weight of the bar and applying maximal or submaximal efforts. Cardiovascular parameters (pulse pressure, mean blood pressure, heart rate), rate of perceived exertion, kilograms, and number of repetitions served to monitor psychophysiological acute variations. Twenty physically active males (25.55 ± 4.75 y.o.) underwent two sessions (one for familiarization and one for the experimental trial). In the experimental session, ocular and cardiovascular pre-exercise measurements were taken. Then, two sets using WP and two using EB attached to the bar with the same load were performed by each subject in random order. Immediately after finishing each set, the subjects rated perceived exertion, and cardiovascular and ocular measurements were taken, in this order. An ANOVA with post-hoc LSD evaluated differences between sets. IOP significantly decreased ($p < 0.001$, $\eta p^2 = 0.513$), and MOPP ($p < 0.001$, $\eta p^2 = 0.413$) and cardiovascular variables significantly increased due to the exercise effect; CCT changes were non-significant. No significant effect of the material, level of effort, or their interaction was observed in the IOP and MOPP ($p > 0.05$). EB permitted more repetitions to be performed and led to non-significantly lower post-exercise IOP values (effect size [*d*] compared to resting 0.79 and 1.00) in comparison to WP ($d = 0.73$–0.74). IOP and ocular and systemic hemodynamic responses are similar when using EB instead of WP to load the bar, with EB allowing a larger number of repetitions. Data presented in this paper may help with the prescription of resistance training for people with glaucoma risk factors.

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Blood pressure

INTRODUCTION

Resistance exercise has been shown to acutely influence parameters of ocular physiology which are strongly related to ocular health, specifically ocular perfusion pressure (OPP) and intraocular pressure (IOP) [1–4]. OPP represents the blood flow entering the eye, which is, in turn, conditioned by the IOP [5]. There is still no consensus on whether resistance exercise acutely increases [6–10] or decreases IOP [11–17]. To the best of our knowledge, only one study has analysed IOP adaptations after four weeks of an upper-body resistance-exercise programme using loads between 40 and 60% of one-repetition maximum (1RM) and found significant decreases in basal values [18].

Numerous devices can be used to enhance the positive effects of resistance exercise [19]. Specifically, elastic bands (EB) are increasing in popularity for both health and physical performance [20–22] due to inducing similar adaptations to traditional resistances [23, 24] and providing optimal resistance across the entire range of motion when EB are attached to the bar for squat exercises (reduced weight during the lowest phases of the range of motion and increased at the upper phases) [25–27]. As far as we know, no previous research has investigated the different acute adaptations that may occur in ocular parameters when using EB instead of weight plates (WP) to load the bar in squats.

It is important to understand that in the deepest phases of the squat a large increase in difficulty occurs, which increases the effort of the core and respiratory muscles [28]. This is related to augmented intrabdominal and intrathoracic pressure [28] and may decrease the venous return through the vena cava. This increases the choroidal volume and episcleral venous pressure and thereby ensures an elevation in IOP [1, 2]. Given that the EB reduce the load throughout this biomechanically disadvantageous region of the movement [26] due to their elongation coefficient [25], the question arises whether the use of EB in resistance exercises could generate different responses in ocular parameters compared to conventional resistance (e.g., weight plates).

The purpose of this study was to analyse IOP, mean ocular perfusion pressure (MOPP), and other ocular health-related parameters after a squat exercise protocol using elastic bands or weight plates to load the bar and performing maximal or submaximal efforts. Bearing in mind the weight reduction that happens with elastic bands in the lower phases of the squat movement, we hypothesize that this material will allow for lower IOP values and higher MOPP than weight plates.

MATERIALS AND METHODS

This quasi-experimental study assessed the changes in ocular health-related parameters after performing squats on a Smith machine considering the use of WP or EB to load the bar and maximal or submaximal efforts. Besides the main variables (IOP and MOPP), central corneal thickness (CCT) was measured to assess whether this parameter may condition IOP behaviour [3,29]. Rate of perceived exertion (RPE), heart rate (HR), mean blood pressure (MBP), and pulse pressure (PP) were used to characterize the cardiovascular adaptations to the exercise [19]. The four squat sets were as follows:

Sets that used weight plates: [1] maximum number of repetitions with 75% of one repetition maximum (1RM); [2] 9 repetitions (submaximal) with 75%1RM.

Sets that used elastic bands: [3] maximum number of repetitions with 75%1RM; [4] 10 repetitions (submaximal) with 75%1RM load.

A percentage of 1RM commonly employed in resistance training (75%1RM) was used [30, 31]. The pertinent kilograms were added to the bar with WP (28 mm cast iron plates from 0.50 to 20 kg; Domyos, France) or EB (looped CLX elastic bands; TheraBand, Akron, OH, USA) at the standing position of each subject. A researcher weighed the bar at this point using a 100 g precision scale (9179 SV3R; Salter, United Kingdom) to ensure the weight for each set with EB. Repetitions for the submaximal sets (Sets 2 and 4) were established at 9 with WP and 10 with EB due to observing that subjects could perform 10 or more repetitions with WP and many more than 10 repetitions with EB in the pilot studies.

Subjects

A sample size of 19 participants was determined by a power analysis (G*Power 3.0; [32]) assuming an α of 0.05, a power level of 0.8, an effect size of f(V) = 0.87 as obtained in the pilot studies, and a non-sphericity correction of e = 1. Inclusion criteria were: 1) younger than 40 years, 2) experience with strength training for at least 6 months and performing at least 2 days per week of lower limb training including squats, 3) no musculoskeletal health issues, 4) normal visual health, and 5) no history of ocular disease or surgery. All participants had a baseline IOP $\leq$ 21 mmHg, systolic blood pressure (SBP) between 90 and 140 mmHg, diastolic blood pressure (DBP) between 60 and 90 mmHg, and PP $\leq$ 65 mmHg, excluding possible cardiovascular and ocular disorders [33, 34].

As a result, of the 25 recruited, only 20 physically active males met the criteria and voluntarily participated in this study (mean age: 25.55 ± 4.75 years, 95% confidence interval (CI) [23.84–28.00]; body mass: 75.67 ± 9.02 kg, 95% CI [71.45–79.89]; body mass index (BMI): 24.04 ± 2.11 kg/m^2, 95% CI [23.20–25.08]; body fat: 10.19 ± 2.29%, 95% CI [9.32–11.38]; squat 1RM: 126.53 ± 24.62 kg, 95% CI [116.32–138.26]; ratio 1RM-body-weight (relative strength): 1.68 ± 0.35, 95% CI [1.53–1.84]). All participants were instructed to avoid alcohol consumption and vigorous exercise for 24 h before any of the sessions. They were asked to sleep for at least 8 h, not to consume stimulants or smoke, not to drink more than 1 L of liquids [2], and not to perform prolonged near-viewing activities in the 3 h before the trials [35].

Procedures

All measurements were conducted in the same laboratory by the same researchers (one optometrist, and two sports scientists) at the Optometric Clinic "Fundació Lluís Alcanyís" from the University of Valencia (Spain). All data were collected in a thermoneutral environment (~22ºC and ~60% humidity), under the same lighting, and between 10:00 h and 13:00 h as the IOP is more stable within this time period [3]. One session for assessment and familiarization and one experimental trial to evaluate all dependent variables were carried out separated by 48 h. Both sessions lasted around 90 minutes.

In the familiarization session, the participants signed the consent form and filled in the demographic questionnaire and guarantee of data confidentiality. They also underwent a physical and visual examination to ensure they complied with the inclusion criteria and to assess their squat technique. Anthropometric measurements were obtained with a height rod (IP0955; Invicta Plastics Limited, Leicester, England) and a bioelectrical impedance scale (Body Composition Analyzer BF-350; Tanita Corporation, Tokyo, Japan). BMI was calculated as weight [kg]/(height [m])^2. At this point, the standardized warm-up was started, including joint mobility, bodyweight exercises (including squats), jogging, and dynamic stretching. As a part of the specific warm-up, participants were instructed on how to perform the squats at the correct movement tempo (see "Squat exercise" section) and how to use the RPE scales [36, 37]. After the warm-up, participants performed the RM testing. Before the testing, three approximation sets were performed: first, one set of 20 repetitions without additional weight (the bar weighed 20 kg), and then two more sets of 15 and 12 submaximal repetitions, out of 20 and 15 RM, respectively. Loads for these submaximal sets were selected according to the participant's self-perception and researcher experience. Finally, a fatigue test with submaximal loads using WP was carried out at the study-specific squat tempo. This procedure consists of performing between 8 and 12 maximal repetitions and introducing the repetitions performed and the kilograms used in a formula [38–41]. If a participant performed more than 12 or less than 8 repetitions, the load was modified, and another set was performed. O'Connor or Brzycki formulas were used to obtain the load for 1RM. After appropriate rest, the RM obtained in the formula was tested and adjusted if necessary. Percentages were calculated for 75%1RM. At least a five-minute rest was allowed between sets; more time was permitted depending on the perception of the subjects [42].

At the beginning of the second session, baseline measurements of each variable were taken. After the warm-up, each set was performed in a random order (https://www.random.org/lists/). Immediately after the exercise, the researcher in charge recorded the number of repetitions and subjects reported RPE (less than 5 seconds) while sitting to undergo cardiovascular direct measurements (SBP, DBP, and HR; 30–40 seconds). Ocular measurements (IOP and CCT) were uniformly started 60 seconds after finishing each set. The physiological measurements were carried out in an adjacent space separated from the Smith machine by a partition screen to blind the researcher in charge. At least a five-minute rest was given between sets and water intake was avoided to prevent IOP changes due to hydration [1]. Constant feedback was used in both sessions to ensure proper execution and to encourage maximum effort [43].

Squat exercise

A high-bar back squat to a parallel depth [22,44] was performed in a Smith machine (Multipower Smith Machine Powerline PSM144X; Body-Solid, USA). The stance width was established between the hips and shoulders. Shoes were used but no weightlifting belts or knee wraps were permitted. The tempo consisted of an inhalation-coordinated eccentric phase lasting two seconds [45] with a pause of one second at the deepest point and an exhalation-coordinated maximum speed concentric phase (4 seconds for a complete squat). The Valsalva manoeuvre was avoided due to its influence in IOP [1–4] by asking participants to perform audible breathing. A metronome (Metronome Beats v.4.4.0, Stonekick, London, England) was used at 60 bpm to standardize the movement tempo. The depth was adjusted with a horizontal elastic band. The participant had to touch the band (midthigh) in every repetition.

Ocular measurements

IOP and CCT were measured in mmHg and microns, respectively, with a validated non-contact tonometer [46,47]. The Auto Kerato-Refracto-Tonometer TRK-1P (Topcon, Japan) automatically compensates for the corneal thickness. The intraclass correlation coefficient (ICC) of the measurements was 0.91 (coefficient of variation (CV)=6.24%) for the IOP and 0.93 (CV=0.95%) for the CCT. Measurements were taken in both eyes in the pilot study. Right eye measurements were used since no significant difference was observed between the eyes.

MOPP was calculated in mmHg using the formula MOPP=2/3(MBP)–IOP [4,34]. The results showed an ICC of 0.89 and a CV of 6.68%.

Cardiovascular measurements

Cardiac measurements (SBP, DBP, and HR) were performed using a digital automatic blood pressure monitor (M6W HEM-7213-E (V), Omron, Japan) with an ICC of 0.90 and CV of 5.49% for the SBP, 0.86 and 3.77% for the DBP, and 0.91 and 6.05% for the HR. PP (mmHg) was calculated as SBP–DBP, and MBP (mmHg) as DBP+1/3(PP) [34].

Perceived effort measurements

RPE was measured with the OMNI-RES [35] and OMNI-RES for EB [36]. Previous studies can be consulted for further details on how to apply these scales [47–49].

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Ethics

The study was conducted in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Permission was provided by the Ethics Committee on Human Research of the University of Valencia (H1499867368458). Data reported in the present study form part of a research project investigating different ways of applying elastic resistance in squat performance. Previous data from this project have already been published [22, 43]. All participants voluntarily agreed to participate and were free to withdraw from the study at any time. They signed an informed consent form including a guarantee of data confidentiality.

Statistical analyses

Statistical analyses were performed using commercial software IBM SPSS Statistics for Macintosh (Version 26.0; IBM Corp., Armonk, NY). The normality of data distribution was assessed using the Shapiro-Wilk test. All physiological variables showed a normal Gaussian distribution ($p > 0.05$). RPE followed a non-normal distribution ($p \leq 0.05$).

To assess differences and evaluate the influence of the material and the type of effort on the dependent variables, two approaches were employed: 1) a two-way ANOVA with the material (EB and WP) and the level of effort (maximal and submaximal) as the within-subject factors and, 2) an analysis of variance (ANOVA) of repeated one-way measurements to evaluate differences between the resting values and the exercise sets. All the cases complied with Mauchly's sphericity assumption. The effect size was evaluated with eta partial squared (ηp^2), where $0.01 < \eta p^2 < 0.06$ constitutes a small effect, $0.06 \leq \eta p^2 \leq 0.14$ medium, and $\eta p^2 > 0.14$ a large effect. Pairwise post-hoc comparisons were carried out using the least significant difference correction (LSD). The effect size was calculated as Cohen's d with Hedges corrections [51]. This value is reported as unbiased Cohen's d (d_{unb}) [52], with $d_{unb} < 0.50$ constituting a small effect, $0.50 \leq d_{unb} \leq 0.79$ moderate, and $d_{unb} \geq 0.80$ a large effect [53].

The test-retest relative reliability of the instruments was assessed in a subsample of 10 subjects (2 measurements per subject) calculating the ICC [54]. ICC was interpreted as poor (< 0.40), moderate (0.40–0.59), good (0.60–0.79) or excellent (≥ 0.80) [55]. The absolute reliability was verified with the coefficient of variation (CV) using the formula: (standard error of measurement (SEM)/mean of both measurements)x100; SEM is the standard deviation of the difference between the two measurements divided by the square root of the number of measurements per subject [56].

Results are reported as mean ± standard deviation [95% confidence interval (CI)] and as the median and interquartile range (IQR) for the non-normal variables. The significance level was established at $p \le 0.05$.

RESULTS

External load

The 75%1RM used by the subjects for the squat protocol was 95.33 ± 18.08 kg, 95% CI [87.38–102.97]. As previously mentioned, the number of repetitions for the submaximal sets was established at 9 and 10 with WP and EB, respectively. The number of repetitions for the maximal sets was 10.15 ± 0.81 repetitions, 95% CI [9.85–10.55] for the set with WP and 18.40 ± 4.86 repetitions, 95% CI [16.13–20.67] for the set with EB.

Ocular variables

The results of the ocular variables are displayed in Table 1. Significant variations were detected in the IOP ($F[4,76] = 19.98$, $p < 0.001$, $\eta p^2 = 0.513$) and MOPP ($F[4,76] = 15.13$, $p < 0.001$, $\eta p^2 = 0.443$) when including the pre-exercise value in the analysis, but not in the CCT ($F[4,76] = 0.372$, $p = 0.828$, $\eta p^2 = 0.02$). Pairwise post-hoc comparisons showed that IOP and MOPP significantly decreased and increased compared to resting levels, respectively. The effect of the material ($F[1,19] = 1.78$, $p = 0.19$, $\eta p^2 = 0.086$), the level of effort ($F[1,19] = 1.15$, $p = 0.29$, $\eta p^2 = 0.057$), and their interaction ($F[1,19] = 1.20$, $p = 0.28$, $\eta p^2 = 0.060$) in the IOP, were non-significant. Similar results were obtained for the MOPP (material: $F[1,19] = 0.852$, $p = 0.37$, $\eta p^2 = 0.043$; level of effort: $F[1,19] = 0.039$, $p = 0.84$, $\eta p^2 = 0.002$; interaction: $F[1,19] = 0.069$, $p = 0.79$, $\eta p^2 = 0.004$).

TABLE 1. Ocular outcomes for each of the four squat sets.

Condition	IOP (mmHg)	MOPP (mmHg)	CCT (microns)
Baseline	15.05 ± 3.22* [13.54–16.56]	43.45 ± 5.80* [40.74–46.17]	562.40 ± 29.19 [548.74–576.06]
Set 1 (Max75%1RMWP)	12.85 ± 2.82$^{(3)}$ [11.53–14.17]	53.05 ± 8.49 [49.08–57.03]	561.15 ± 30.35 [546.95–575.35]
Δ%	14.62	22.09	0.22
Cohen's d_{unb}	0.73	1.27	0.04
Set 2 (Submax75%1RMWP)	12.80 ± 2.82 [11.48–14.12]	52.59 ± 8.44 [48.64–56.54]	562.65 ± 29.50 [548.84–576.46]
Δ%	14.95	21.03	0.04
Cohen's d_{unb}	0.74	1.21	< 0.01
Set 3 (Max75%1RMEB)	12.30 ± 2.18$^{(1)}$ [11.28–13.32]	51.98 ± 8.34 [48.07–55.88]	561.80 ± 28.59 [548.42–575.18]
Δ%	17.95	19.62	0.11
Cohen's d_{unb}	1.00	1.14	0.02
Set 4 (Submax75%1RMEB)	12.75 ± 2.55 [11.56–13.94]	52.10 ± 6.36 [49.12–55.07]	562.00 ± 28.84 [548.50–575.50]
Δ%	15.28	19.89	0.07
Cohen's d_{unb}	0.79	1.36	0.01

Note: Values are presented as mean ± standard deviation [95% confidence interval]. Percentage of variation (Δ%) and effect size (Cohen's d unbiased; $d_{unb} < 0.50$ small, $0.50 \le d_{unb} \le 0.79$ moderate, and $d_{unb} \ge 0.80$ large) compared to baseline values are displayed. *: Statistically significant difference compared to the rest of the conditions. $^{1, 2, 3, 4}$: Significant difference ($p < 0.05$) or a trend ($p > 0.05$ to $p < 0.13$; if the number is in brackets), with the condition 1, 2, 3, or 4, respectively; Max: maximum number of repetitions; Submax: submaximal repetitions; %1RMWP: percentage of one repetition maximum with weight plates; %1RMEB: percentage of one repetition maximum with elastic bands; IOP: intraocular pressure; MOPP: mean ocular perfusion pressure; CCT: central corneal thickness.

TABLE 2. Cardiovascular and perceived effort values for each of the four squat sets.

Condition	PP (mmHg)	MBP (mmHg)	HR (bpm)	RPE
Baseline	58.58 ± 8.04* [55.16–62.16]	87.75 ± 6.97* [84.49–91.01]	63.95 ± 11.27* [59.05–69.21]	-
Set 1 (Max75%1RMWP)	73.42 ± 17.40 [66.26–81.42]	98.85 ± 11.18 [93.62–104.08]	105.26 ± 16.76 (3),4 [97.95–112.89]	8.55 ± 0.88 2,4 [8.14–8.96]
Δ%	26.37	12.65	65.05	Median 8.5
Cohen's d_{unb}	1.05	1.14	2.77	IQR: 1
Set 2 (Submax75%1RMWP)	72.25 ± 18.39 [63.00–78.47]	98.08 ± 11.66 [92.63–103.54]	104.47 ± 17.84 3 [97.00–112.16]	7.55 ± 0.99* [7.09–8.01]
Δ%	23.73	11.78	63.09	Median: 7
Cohen's d_{unb}	0.80	1.03	2.61	IQR:1
Set 3 (Max75%1RMEB)	72.20 ± 12.65 [65.74–76.89]	96.42 ± 11.97 [90.82–102.02]	110.89 ± 23.80 (1),2,4 [100.53–121.05]	8.65 ± 0.93 2,4 [8.21–9.09]
Δ%	23.64	9.88	74.28	Median: 9
Cohen's d_{unb}	1.15	0.85	2.42	IQR:1
Set 4 (Submax75%1RMEB)	73.21 ± 12.68 [68.21–79.58]	97.27 ± 8.68 [93.20–101.33]	100.47 ± 16.88 1,3 [93.42–108.26]	6.50 ± 1.24* [5.92–7.08]
Δ%	25.61	10.85	57.10	Median 6
Cohen's d_{unb}	1.32	1.16	2.44	IQR: 1

Note: Values are presented as mean ± standard deviation [95% confidence interval]. Also, median and interquartile range (IQR) are displayed for rate of perceived exertion (RPE) as it is a non-normal variable. Percentage of variation (Δ%) and effect size (Cohen's d unbiased; d_{unb} < 0.50 small, 0.50 ≤ d_{unb} ≤ 0.79 moderate, and d_{unb} ≥ 0.80 large) compared to baseline values are displayed. *: Statistically significant difference compared to the rest of the conditions; 1, 2, 3, 4: Significant difference ($p < 0.05$) or a trend ($p \geq 0.05$ to $p < 0.13$; if the number is in brackets), with the condition 1, 2, 3, or 4, respectively; Max: maximum number of repetitions; Submax: submaximal repetitions; %1RMWP: percentage of one repetition maximum with weight plates; %1RMEB: percentage of one repetition maximum with elastic bands; PP: pulse pressure; MBP: mean blood pressure; HR: heart rate.

Cardiovascular parameters and perceived effort

Significant differences were observed in all the cardiovascular variables (PP: $F[4,76] = 7.94$, $p < 0.001$, $\eta p^2 = 0.295$; MBP: $F[4,76] = 8.88$, $p < 0.001$, $\eta p^2 = 0.318$; HR: $F[4,76] = 59.44$, $p < 0.001$, $\eta p^2 = 0.758$). Post-hoc testing revealed that while all the variables significantly increased compared to baseline values, differences among sets only appeared in HR and RPE, as can be seen in Table 2. Regarding the HR, an influence of the level of effort ($F[1,19] = 8.12$, $p = 0.01$, $\eta p^2 = 0.299$) and the interaction material*level of effort ($F[1,19] = 5.44$, $p = 0.03$, $\eta p^2 = 0.223$) was observed, while the influence of the material was non-significant. An influence of the material ($F[1,19] = 7.946$, $p = 0.01$, $\eta p^2 = 0.295$), the level of effort ($F[1,19] = 167.83$, $p < 0.001$, $\eta p^2 = 0.898$), and its interaction ($F[1,19] = 15.55$, $p < 0.001$, $\eta p^2 = 0.450$) was observed on the RPE.

DISCUSSION

Based on the ocular and systemic responses to a squat exercise protocol, this investigation examined whether elastic bands may modulate these physiological acute adaptations to resistance exercise. Overall, the outcomes of this research were that: 1) IOP significantly decreased and 2) OPP and the cardiovascular values (PP, MBP, HR) significantly increased after all the exercise sets compared to pre-exercise values. Although the study hypothesis could not be confirmed and no effect of the material was observed in the ocular variables, the largest drop in IOP (2.70 mmHg) was observed after a maximal effort with EB at 75%1RM (see Table 1). Empirical evidence was found indicating that EB facilitate a higher number of repetitions (see "Results – External load" section) while maintaining similar pulse pressure and mean blood pressure (see Table 2), which have been related to cardiovascular [33] and ocular health [34]. Also, the rate of perceived effort and HR were not different between performing a mean of 10 repetitions with weight plates and a mean of 18 repetitions with elastic bands both at 75%1RM.

Considering what has been mentioned above, it is worth discussing the outputs of this research under the light of other empirical experiences, which addressed the influence of the external load and other physiological parameters on the IOP. However, this evidence does not contemplate variable resistance as a method of loading the bar.

Squatting with EB reduces the weight at the bottom phases of the squat, during which a mechanical disadvantage occurs [25,26]. Beyond this point, EB add progressively more resistance/weight until the end of the movement. Thus, exercising with EB can increase the load in the region of the range of motion that is more mechanically effective, accompanied by reduced loads in the less efficient range [22,25,26]. This feature of the EB allowed subjects to perform more repetitions, which is useful to promote muscle adaptations [16,27,57]. The combination of all these facts argues in favour of the incorporation of EB in resistance training programmes. Additionally, the use of EB in this study provoked similar values of post-exercise IOP as the use of WP did (maximal effort: mean difference 0.55 mmHg, 95%CI [-0.12-1.22]; p=0.10; d_{unb}=0.210; submaximal effort: mean difference 0.05 mmHg, 95%CI [-0.62-0.72]; p=0.87; d_{unb}=0.018). This combination of findings suggests that EB is an appropriate device to load the bar for squat exercises when looking for high volumes and conservative ocular responses. To support these findings, independent variables included in our study and their influence on IOP are discussed below.

The independent variable of the external load addressed by the expert literature as having major relevance for the changes in ocular physiology is the intensity (weight). Most of the current literature reports higher IOP values with higher intensities [6,7,9,14,16,17,58]. Oppositely to the intensity, a higher volume of repetitions has been related to lower IOP values [6,8,14,16]. In our study, the set with a larger number of repetitions (maximum effort at 75%1RM with EB) provoked the lowest IOP (12.30 mmHg), although the differences with the rest of the sets were not significant. Supporting the influence of the volume on IOP, differences were not found between performing 9 and 10.15 repetitions with WP or between 9 and 10 repetitions with WP and EB, respectively. Lower IOP values in response to a larger number of repetitions may be due to physiological acute adaptations to higher volumes of exercise, such as modifications in plasma pressures, biochemical responses [2–4,27], and higher levels of blood lactate [16,59]. Understanding that lower intensities allow for higher volumes (and higher intensities for lower volumes) [60], it is important to address the possible influence of the level of effort within the ocular acute adaptations to resistance exercise.

The level of effort (i.e. number of repetitions performed out of the maximum possible) has been shown to influence IOP and OPP behaviour, with certain controversy regarding the safety of performing maximal efforts [8,12,16]. While one study reported reductions in IOP after maximum number of repetitions at 60%1RM [16], other authors recommended not including maximal efforts when looking forward to avoiding IOP increases and OPP decreases [8]. Our results indicate that no difference existed between performing a maximal or submaximal effort at 75%1RM with WP (m.d. 0.05 mmHg, 95%CI [-0.59-0.69], p=0.87, d_{unb}=0.017) or EB (m.d. 0.45 mmHg, 95%CI [-0.15-1.05], p=0.13, d_{unb}=0.18).

All cardiovascular values were significantly modified from pre-exercise values. However, differences between sets only emerged in RPE and HR; no influence of the EB compared to WP was observed for the BP values (MBP and PP), as happened with the MOPP. Bearing in mind these results and while caution should be applied, resistance training with elastic bands could be performed by people with hypertension risk just as it can be performed with WP [61,62]. It must be noted that the set which caused the highest HR (maximal effort at 75%1RM with EB), coinciding with the largest volume of repetitions, was also the set with the lowest IOP values, although, and as previously mentioned, the differences were not significant. This fact is probably related to the total volume of work, which increases HR [63] and modulates IOP responses [2–4]. As could be expected, the maximal sets were perceived as harder than the submaximal sets. It is also worth highlighting that a maximal effort at 75%1RM with EB was not perceived as harder than with WP, while the set with EB presented a greater number of repetitions.

All the aforementioned variations may be due to different physiological, homeostatic mechanisms. First, we can state that IOP variations were not mediated by CCT changes, as this variable remained stable within all the conditions. This confirms the findings of Read & Collins [64] on stable CCT values after moderate-intensity bicycle ergometer exercise and supports the hypothesis of Wylęgała et al. [3] that the increases reported in CCT after high-altitude climbing might be attributed to low oxygen concentration at higher altitudes rather than to the exercise effect. As for the OPP, exercise-induced changes seem to be mediated by the BP rather than by the IOP, which confirms previous research on the relationship between OPP and BP [2–4,34,65].

Limitations and future directions

Although all the procedures and analyses were carefully designed and carried out, some limitations should be listed. Firstly, validated air-puff tonometry was chosen as it is easy to use, and does not require the use of anaesthesia [46,47]. However, future studies should standardize a method of continuous IOP measurement [66] and thus, this study should be replicated continuously monitoring the IOP during the squats and for a prolonged period after the exercise to perform a daily curve; diagnosed or suspected glaucoma patients and elderly subjects should be included with a greater sample size. Also, and even though the order of the sets was randomized (across subject counterbalance), future studies should test all the sets in a complete counterbalanced order to be able to determine the effects of the order of exercises on the ocular responses. BP and OPP were estimated with formulas as direct measurements have been proven difficult to carry out in laboratory practices [65]. However, HR significantly changed between sets and this may modulate the fraction of systole (which is used in the MBP formula as the constant) [67]. Also, a method to equalise the weight between EB and WP, as proposed in recent expert literature [22], would help to better understand ocular responses to both materials. It would be interesting to evaluate the kilograms used throughout the range of motion with EB to compare the effects of using the same mean weight with both materials. In this regard, in different pilot studies we performed, we found a descent in the load of about 40% from the standing position to the lowest point of the execution (in our pilot studies located at 81.12±3.74 knee joint angle degrees). Finally, future studies should apply different intensities and account for differences in muscle activation between WP and EB.

Practical implications

The evidence presented highlights the potential practical applications of using elastic bands to achieve a higher number of repetitions while maintaining safe levels in the analysed ocular health-related and cardiac parameters. We could encourage the professionals interacting with people with glaucoma risk factors to instruct their clients to control the technique, movement tempo, and avoid the Valsalva manoeuvre. Bearing this in mind, both materials studied (elastic bands and weight plates) could be indistinctly used depending on the aims of the training programme without obtaining significant differences in the ocular variables analysed.

CONCLUSIONS

The most notable finding was that, although the elastic bands allow for more repetitions and add less resistance in the lowest phases of the range of motion than the weight plates, the intraocular pressure, mean ocular perfusion pressure, pulse pressure, and mean blood pressure did not significantly differ. Data from this study indicate that post-exercise IOP is lower, and MOPP higher compared with resting values, after maximal or submaximal efforts, and both with EB and WP. This combination of findings provides some support for the usefulness of EB to perform resistance exercises and, while further research is needed in this regard, suggests that ocular health can be preserved with their use. This research contributes to the multidisciplinary collaboration between optometrists, ophthalmologists, and strength and conditioning professionals for the management and prevention of glaucoma.

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Conflict of interest declaration

The authors declare no competing interests. The current study did not receive any funding from neither public, commercial, nor not-for-profit agencies or entities.

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9.2 Articles published by the doctoral candidate not included in the compendium but directly associated with the present doctoral thesis

9.2.1 Scientific articles

Flandez, J., **Gene-Morales, J.,** Juesas, A., Saez-Berlanga, Á., Miñana, I., & Colado, J. C. (2020). A systematic review on the muscular activation on the lower limbs with five different variations of the deadlift exercise. *Journal of Human Sport and Exercise*, *15*(Proc4), S1262–S1276. https://doi.org/10.14198/jhse.2020.15.Proc4.27

Flandez, J., **Gene-Morales, J.,** Modena, N., Martin, F., Colado, J. C., & Gargallo, P. (2020). Effects of power resistance training program with elastic bands on body composition, muscle strength and physical function in older women. *Journal of Human Sport and Exercise*, *15*(Proc4), S1322–S1337. https://doi.org/10.14198/jhse.2020.15.Proc4.30

Hammami, R., **Gene-Morales, J.,** Abed, F., Selmi, M. A., Moran, J., Colado, J. C., & Rebai, H. H. (2021). An eight-weeks resistance training programme with elastic band increases some performance-related parameters in pubertal male volleyball players. *Biology of Sport, 39*(1), 219–226. https://doi.org/10.5114/biolsport.2021.101601

9.2.2 Manuscripts under review

Gene-Morales, J., Colado, J. C., Pérez-Castilla, A., García-Ramos, A., Redondo, B., Jiménez, R., Vera, J., & Martin-Rivera, F. (2021). Acute intraocular pressure responses to resistance training in combination with blood flow restriction. *Manuscript Submitted for Publication*.

9.2.3 Congress communications

Flandez, J., Gargallo, P., **Gene-Morales, J.,** Modena, N., Martin, F., & Colado, J. C. (2020). *Effects of a power strength training with elastic bands on body composition, physical function, and muscle strength in older women*. Costa Blanca Sport Science Summer Event, Alicante, Spain.

Flandez, J., **Gene-Morales, J.,** Juesas, A., Gargallo, P., Miñana, I., & Colado, J. C. (2020). *Muscular activation on the lower limbs with five different variations of the squat exercise.* Costa Blanca Sport Science Summer Event, Alicante, Spain.

Flandez, J., **Gene-Morales, J.,** Juesas, A., Saez-Berlanga, A., Miñana, I., & Colado, J. C. (2020). *Muscular activation on the lower limbs with five different variations of the deadlift exercise.* Costa Blanca Sport Science Summer Event, Alicante, Spain.

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Gargallo, P., **Gene-Morales, J.,** Navarro, J., Baños, R. M., Casaña, J., Saez, G., & Colado, J. C. (2020). *Differential effects of multi-component, power, and traditional resistance training on health-related quality of life, anxiety, and depressive symptoms in older risk in older women*. 6º Congreso Internacional de Readaptación y Prevención de Lesiones en la Actividad Física y el Deporte y 4º Congreso Internacional de Salud y Ejercicio Físico, Valencia, Spain.

Gene-Morales, J. (2020). *Respostas da pressao intra-ocular e de outros parâmetros oculares ao exercício: Uma revisao*. 1º Encontro Internacional da Visao e Desporto e XXIII Congresso de Optometria, Oeiras, Portugal.

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Llorca, V., **Gene-Morales, J.,** Valencia, P., Llobell, R., & Colado, J. C. (2020). *Análisis de variables de rendimiento durante la sentadilla con carga moderada realizada con resistencia constante frente a resistencia variable*. V Congreso Internacional Optimización del Entrenamiento y Readaptación Físico-Deportiva, Sevilla, Spain.

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9.3 Other scientific contributions authored by the doctoral candidate published during the development of the present doctoral thesis

9.3.1 Scientific articles

Aguilar-Navarrete, J., Flández, J., **Gene-Morales, J.,** & Colado, J. C. (2020). Critical incidents which limit performance of Chilean University rowers who won a medal in the Pan American Games of Lima 2019. *Journal of Human Sport and Exercise, 5*(1), 61–75. https://doi.org/10.14198/jhse.2022.171.16

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Torkamaneh, S., **Gene-Morales, J.**, Flandez, J., Yadac, M., Sidiq, M., Rafieian-Kopaei, M., & Colado, J. C. (2021). Preventive effects of garlic and lemon extract combined with aerobic exercise on blood metabolic parameters and liver enzymes. *Journal of Human Sport and Exercise, 16*(2proc), S640-650. https://doi.org/10.14198/jhse.2021.16.Proc2.49

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Journal of Human Sport and Exercise, 16(2proc), S619–S629. https://doi.org/10.14198/jhse.2021.16.Proc2.47

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9.3.2 Manuscripts under review

Hammami, R., **Gene-Morales, J.,** Hanen, W., Rebai, H., & Colado, J. C. (2021). Effects of two different eight-week instability resistance training programs on strength, power, and balance of prepubertal weightlifters. *Manuscript under Review*.

Hammami, R., Selmi, M. A., **Gene-Morales, J.**, Juesas, A., & Colado, J. C. (2021). Effects of one versus two games a week on subjective training load, wellness, and injury rate in male elite soccer players. *Manuscript under review*.

Jiménez-Martínez, P., Ramírez-Campillo, R., Alix-Fages, C., **Gene-Morales, J.,** & Colado, J. C. (2021). Resistance training effects on adipokines in type 2 diabetes mellitus: A systematic review. *Manuscript under Review*.

Useche, S. A., **Gene-Morales, J.**, Alonso, F., O'Hern, S., & Stephens, A. N. (2021). Unsafety on two wheels, or social prejudice? Proxying behavioral reports on bicycle and e-scooter risky riding – a mixed method study. *Manuscript under Review*.

9.3.3 Congress communications

Flandez, J., Vargas, R., González, M., Arismendi, A., **Gene-Morales, J.,** Juesas, Á., & Colado, J. C. (2021). *The importance of Physical Education and Health being a core subject. Arguments and postures concerning the curricular modifications.* Costa Blanca Sport Science Spring Event, Alicante, Spain.

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Torkamaneh, S., **Gene-Morales, J.**, Juesas, Á., Flandez, J., Colado, J. C., & Rafieian-Kopaei, M. (2020). *Effects of 6 weeks intake Berberis Vulgaris L in combination with resistance and aerobic exercise on the lipid profile in obese male rats.* Costa Blanca Sport Science Autum Event, Alicante, Spain.

9.4 Research stays

The doctoral candidate has completed three research stays in the following destinations:

- Leon Levine Hall, Department of Health & Exercise Science, Appalachian State University, Boone, North Carolina, United States of America. Supervisor: Travis Triplett, PhD. Chair, professor and Physiology of Exercise, Exercise Science Undergraduate Program Director. President of the National Strength and Conditioning Association (NCSA). Date: from 15th July 2019 to 15th September 2019. Duration: 2 months.

- Laboratory of Research in Clinical and Experimental Optometry, Department of Physics, School of Science, University of Minho, Braga, Portugal. Supervisor: Jorge Manuel Martins Jorge, PhD. Associate professor. Date: from 15th June 2021 to 15th July 2021. Duration: 1 month.

- Department of Physical Culture, Faculty of Natural Science, Mathematics and Education, University of Mostar, Mostar, Bosnia and Herzegovina. Supervisor: Mile Ćavar, PhD. Assistant professor. Date: from 6th December 2021 to 10th December 2021. Duration: 1 week.

9.5 Funding

The doctoral candidate has won several research contracts and a grant to do a short research stay:

- Research employment contract within the project “Investigación, desarrollo e innovación en tráfico, transporte, movilidad y seguridad vial”. Ref. CPI-21-163. Oferta pública convocada por resolución de la Universidad de Valencia de 30 de abril de 2021 (DOGV 8999, 12-01-2021). Instituto Universitario de Investigación en Tráfico y Seguridad Vial (INTRAS). Researcher in charge: Francisco Alonso Pla. Duration: July 2021 - October 2021, 4 months.

- Research employment contract within the project “C-Roads Spain”. Ref. CPI-20-116. Oferta pública convocada por resolución de la Universidad de Valencia de 24 de abril de 2020 (DOGV 8809, 12-5-2020). Instituto Universitario de Investigación en Tráfico y Seguridad Vial (INTRAS). Researcher in charge: Francisco Alonso Pla. Duration: July 2020 - June 2021, 1 year.

- Research employment contract within the project “Cátedra sistema de innovación y apoyo a la gestión eficiente y sostenible de la movilidad urbana”. Ref. CPI-18-442. Oferta pública convocada por resolución de la Universidad de Valencia de 24 de abril de 2020 (DOGV 8442, 12-12-2018). Instituto Universitario de Investigación en Tráfico y Seguridad Vial

(INTRAS). Researcher in charge: Francisco Alonso Pla. Duration: March 2019 - June 2020, 1 year.

- Travel grant included within the Erasmus+ KA107 program for staff members and published by "Resolució de 5 de novembre de 2019 del Vicerector d'Internacionalització i Cooperació de la Universitat de València per la qual es convoquen ajudes per a la mobilitat del personal a països associats (no pertanyents a la Unió Europea) en el marc del programa Erasmus+ KA107 per al curs acadèmic 2019-2020". Location: University of Mostar, Mostar, Bosnia and Herzegovina. Duration: 7 days.

9.6 Ethics committee approval

VNIVERSITAT D VALÈNCIA Vicerectorat d'Investigació i Política Científica

D. José María Montiel Company, Profesor Contratado Doctor Interino del departamento de Estomatología, y Secretario del Comité Ético de Investigación en Humanos de la Comisión de Ética en Investigación Experimental de la Universitat de València,

CERTIFICA:

Que el Comité Ético de Investigación en Humanos, en la reunión celebrada el día 7 de septiembre de 2017, una vez estudiado el proyecto de investigación titulado: *"Variaciones en la presión intraocular según intensidad, carga y tipo de material durante el entrenamiento de la fuerza de los miembros inferiores con el ejercicio de la sentadilla", número de procedimiento H1499867368458,* cuyo responsable es D. Juan Carlos Colado Sánchez, ha acordado informar favorablemente el mismo dado que se respetan los principios fundamentales establecidos en la Declaración de Helsinki, en el Convenio del Consejo de Europa relativo a los derechos humanos y cumple los requisitos establecidos en la legislación española en el ámbito de la investigación biomédica, la protección de datos de carácter personal y la bioética.

Y para que conste, se firma el presente certificado en Valencia, a quince de septiembre de dos mil diecisiete.

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