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Original Article

Human body flotation and organic responses to water immersion

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Abstract:
Swimming is a physical activity performed in an environment where human beings are not adapted from an evolutionary point of view. For this reason, swimming for humans is considered an ontogenetic movement and not a phylogenetic one such as walking or running on land. Locomotion into the water has some very specific characteristics for the human being, since the body experiences a situation of hydrostatic microgravity which in most cases enables flotation. Flotation capacity is affected by the physicochemical properties of the water (temperature and osmolarity) and by the body characteristics of the immersed person. In this situation: (1) joints no longer experience the load implied by supporting body weight on land, (2) blood flows more easily, and (3) the type of muscular work is basically concentric. Body balance is other important aspects to take into account, especially in swimmers with amputated limbs or limbs paralysis. Finally, the thermoregulatory response of the human body to changes in water temperature is also considered a useful and extended recovery method.

Key words: swimming, buoyancy, weightlessness, body composition, hydrostatic pressure, water recovery.

Introduction

James Counsilman (1921-2004), one of the most renowned swimming scientists and trainers, wrote in his last book: “We are 65 percent water, so they say, but when humans enter the water it is a foreign element in which we are poorly designed for efficient locomotion … We can only attain top speeds of about six miles per hour, whereas dolphins and some fish reach speeds five times that fast” (Counsilman & Counsilman, 1994). This idea summarizes the situation of human when are immersed in water.

Human locomotion in water is rather inefficient due to, on the one hand, the specific properties of water: a dense, viscous fluid in which it is difficult to apply forces of propulsion and where the hydrodynamic resistance forces are very important. Despite these special properties, animals that have evolved in aquatic media, such as fish or cetaceans are capable of moving efficiently in this medium. On the other hand, animals such as humans that have evolved on land, while able to move inside the aquatic medium, have very low levels of efficiency. The reason for the different aquatic movement efficiency lies on their different morphology. Aquatic animals have bodies shaped for moving under water that make them very hydrodynamically streamlined. They also have flat fins which enable them to create propulsion. Conversely, human beings are shaped with little hydrodynamic streamlining, and moreover their propulsion surface is small and rounded. Thus, human beings’ mechanical efficiency (mechanical work done/net energy consumed) when swimming can barely reach 8 % (Di Prampero, Pendergast, Wilson, & Rennie, 1972), whereas whilst running the human mechanical efficiency varies between 25 % to 35 % (Kaneko, 1990).

To understand human locomotion on water, it is necessary to know the forces that are applied to the swimmer. Figure 1 shows the four forces that dictate how a human being swims: weight force and buoyancy (or flotation force) determine mainly the swimmer’s floatability, while propulsion and drag forces determine the swimming speed.

Even though there are numerous studies that explain the basics of propulsion and drag forces in water, scientific literature is still scarce about the effects of water immersion and buoyancy on the human body. Therefore, the aim of this review was to establish a theoretical background and to highlight the dearth of scientific knowledge addressing this matter.

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Fig. 1. Forces during swimming (Llana, Pérez, Bravo, & Invernizzi, 2010)

Method

For this systematic review, an extensive literature search was conducted using the MEDLINE (PubMed) and SportDiscus electronic databases with no year, gender, age or type of article restriction. The key words used in the online search included “swimming” “aquatic exercise”, “locomotion”, “flotation”, “buoyancy”, “microgravity”, “hydrostatic pressure” and “water recovery”.

Our search yielded 56 articles, and a final selection of 39 articles which were considered relevant was done to fit the objectives of the study. Among the 39 studies, 33 were research articles and the 6 remaining papers were reviews.

Results

WHAT IS FLOTATION?

The flotation of a body in water depends on the vertical forces that are applied at any given moment. At rest, flotation is determined by Archimedes’ principle (3rd cent. B.C), according to which “any object wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object”. This force is called buoyancy (B) or flotation force. As a consequence, when somebody enters the water and remains at rest, their flotation depends on their weight/buoyancy relationship: when buoyancy is greater than weight the person will float and, in the same way, when weight is greater than buoyancy, the person will sink. In the latter situation where the body tends to sink, a person could remain in the water surface only by creating upwards forces equal or greater than the weight force through the movement of their body segments (Cureton Jr, 1930), what is known as active (or dynamic) flotation.

To understand if a human body at rest will float or sink, it is necessary to comprehend the factors influencing the relationship weight/buoyancy: when gravity (g), the volume of the submerged body (v_{body}) and that of displaced water (vwater) are equal (equations 1 and 2), a body’s flotation will be determined by their densities (v_{water} vs v_{body}). As a result, people whose body density is higher than that of water will sink, whereas those of lower densities will float.

$$\text{Eq. 1: Buoyant force} = m_{water}\, g = v_{water}\, \rho_{water}\, g$$

$$\text{Eq. 2: Body weight} = m_{body}\, g = v_{body}\, \rho_{body}\, g$$

Therefore:

$$v_{water} = v_{submerged\ body}$$

$$g = g$$

Water density can vary according to two factors (Timberlake, 2011), temperature and osmolarity (other parameters such as the amount of dissolved gases may also affect the water density, but in such small quantity that for practical purposes they are not taken into account):

1) Temperature: the relationship between density and temperature for distilled water is an “inverse J”. The maximum density of water (1000 kg/m3) is reached at 4 ºC, whereas it decreases slightly to 920 kg/m3 at 0º C, and to 958.3 kg/m3 at 100 ºC. The density of the water at the official temperature established in swimming competitions, 25-28 ºC (FINA rule FR 2.11) (FINA, 2010), is about 987 kg/m3.

2) Osmolarity refers to the amount of solutes dissolved in a liquid. The more solutes, the higher the density, so it is easier to float in the sea than in a lake since the average density of the “salty water” (two thirds of the salts are sodium chloride) of the sea is approximately 1035 kg/m3. In some inner seas such as the Mediterranean, the density is even slightly higher. The most extreme case is the Dead Sea on the border between Israel and Jordan, where the density is as high as 1225 kg/m3. In this sea floatability is so high that some tourist guides claim it to be “a sea where it is impossible to drown”.

The case of the human body density is far complex because its density is not homogenous and there are significant differences among the biological tissues that compose the human body (Clauser, McConville, & Young, 1969). While bone tissue is the densest, ranging between 1400 kg/m3 (cancellous or spongy bone) and

1800 kg/m3 (cortical or compact bone), other tissues such as muscle, tendons or ligaments are slightly denser than water, between 1020 kg/m3 and 1050 kg/m3. The only tissue less dense than water is the adipose tissue with a density of 940-950 kg/m3. These are average values that may vary slightly according to the individual's age, gender and physiological condition.

Based on the densities of the biological tissues, human beings should always sink. Then, why do human beings float? The answer lies in the air existing inside the lungs and the respiratory airways, since the density of the air is eight hundred times lower than the density of water: approximately 1.2 kg/m3 at 20º C (Timberlake, 2011). Hence, the lungs act as a floating system, since during natural breathing 4 to 5 litres of air enter the body, what increases significantly the body volume accompanied by a slight increase in weight of only 0.047 N to 0.058 N (Kreighbaum & Barthels, 1996).

Therefore, human beings' ability to float at rest (passive flotation) largely depends on their ability to expand their thorax upon inhaling (Donoghue & Minnigerode, 1977). As a matter of fact, a test carried out in the University of Valencia (Spain) showed that 100% of the participants (245 caucasian students from the Faculty of Physical Activity and Sport Sciences) floated with maximum inhalation, whereas 99% of the men (194 from 196) and 91.8% of the women (45 from 49) sank after exhalation.

Passive flotation is also different according to gender, age and race (Kenney, Wilmore, & Costill, 2012):

1) Flotation according to gender. On average, women have greater percentage of adipose tissue than men. Between 20 and 39 years of age, men have from 8% to 20% of adipose tissue, compared to 21% to 33% of women (Kenney et al., 2012). This difference in adipose tissue makes women's flotation greater than that of men. Moreover, the anatomic location of the adipose tissue differs according to gender: women usually accumulate more fat in the pelvic region, whereas the abdominal region is the most common area for fat accumulation in men. As a consequence, the distance between the centre of flotation and the centre of gravity is shorter in women and therefore the torque generated is also lower. For this reason, maintaining a horizontal position in water requires less energy for women than for men. As shown in figure 2, the torque varies between 5 and 15 Nm in women and between 10 and 20 Nm in men (Zamparo et al., 1996).

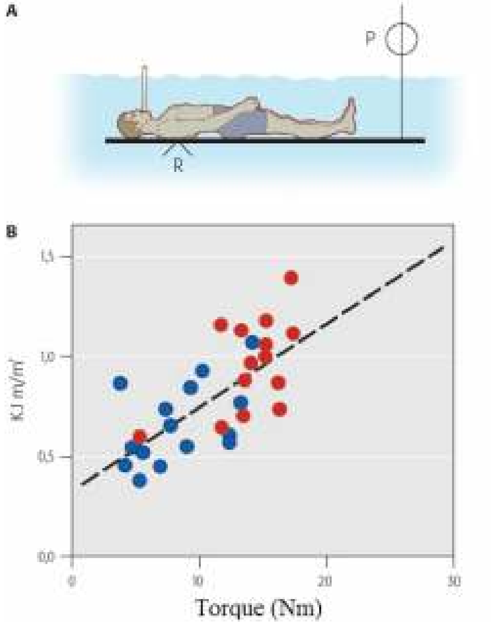

Fig. 2. Above: diagram of how torque is measured in human beings. below: graph of energy expenditure per m2 of body surface area according to torque for the front crawl style in women (blue circle) and men (red circle) of medium level. Adapted from (Zamparo et al., 1996).

2) Flotation according to age. Until puberty there are no significant differences in flotation between boys and girls. However, following puberty the ability to float develops differently. Boys' maximum floatability appears from 10 to 13 years of age due to the accumulation of pre-pubescent adipose tissue (Kenney et al., 2012). After this age, hormonal changes cause the percentage of adipose tissue to decrease and muscular tissue to increase, and therefore flotation in males is notably reduced after reaching 13-14 years. In the case of girls, the hormonal changes due to puberty increase the deposits of adipose tissue, so that their floatability increases after 11-12 years of age.

3) Flotation according to race. It is curious that whereas in running races black athletes dominate all events from 100 m up to marathons, the opposite situation occurs in swimming. One possible explanation is the fact that black people have a lower level of floatability. Earlier investigations on this matter (Lane & Mitchem, 1964) with American students showed that 67.3 % of black students did not float with maximum inhalation, as

opposed to only 8.7 % of Caucasians. Ghesquiere and Kavonen (1971) justified the differences in floatability due to the lower percentage of adipose tissue, greater bone density, and mainly because of the lower lung capacity of the black students compared to the Caucasians (table 1).

Table 1. Forced vital capacity for caucasians vs. black people according to Ghesquiere and Karvonen (Ghesquiere & Kavonen, 1971).

Forced Vital Capacity	(n)	Mean value (l)
Swedish	152	4.980
US Army (white)	392	4.747
US Army (Black)	61	4.116
Zaire	45	3.703
South Africa	120	3.427

THE EFFECT OF MICROGRAVITY ON HUMAN BODY

The hydrostatic microgravity that is experienced in water due to Archimedes' principle takes great load off the body's muscles and its articulations. On land, the force of gravity makes it necessary for the muscles to be constantly working in order to maintain the body's position. The resultant tension, together with the weight of the body structures, is transmitted from segment to segment through the articulations. Over time, some muscle groups, especially the ones that act against gravity, may become hypertonic and the body joints are exposed to overloading and overuse injuries (Bedi, Dolan, Leunig, & Kelly, 2011).

During aquatic immersion, a considerably reduction of weight is experienced due to the buoyancy forces acting on the body. As a result, the activity of the anti-gravity muscles of our body to maintain the posture is not necessary and the load on articulations is considerably reduced, especially on the spine (R. A. Harrison, Hillman, & Bulstrode, 1992; R. Harrison & Bulstrode, 1987). This is the fundamental reason why physical activity on water is recommended for people with articulation problems, especially on the spine, such as degenerative disk disease, degenerative joint disease or scoliosis, stress fractures, total joint replacements, sacroiliac and pubic symphysis dysfunction, etc.

Even when the water level does not completely cover the body, a certain level of hydrostatic hypogravity is also experienced. In table 2, the so-called "hydrostatic weight" (weight of a body immersed in water) is shown according to the water level (R. Harrison & Bulstrode, 1987). This hydrostatic hypogravity is of great relevance in aquatic exercise programs, recommended for certain populations such as people with osteoporosis who have been prescribed physical exercise whilst avoiding high impacts.

Table 2. Reduction in body weight according to the depth of water for two people of 55 kg and 90 kg of mass, both in anatomical position (adapted from (R. Harrison & Bulstrode, 1987)

Water level	% weight released	Hydrostatic weight (kg) for a 55 kg person	Hydrostatic weight (kg) for a 90 kg person
Ankle	4	52.8	86.4
Knee	14	47.3	77.4
Hip	40	33	54
Navel	58	23.1	37.8
Chest	75	13.7	22.5
Neck	90	5.5	9

BODY BALANCE ON WATER

Another important aspect regarding human beings' ability to float is the fact that weight and buoyancy do not act at the same point of the body, what is explained by the difference in densities: the density of water is homogenous whereas that of the human body is not. Thus, weight acts at the person's centre of gravity, generally around the lumbar/pelvic region (Zamparo et al., 1996), whereas buoyancy is applied at the centre of gravity of the volume of water displaced (volumetric centre), in the caudal region of the thorax (Zamparo et al., 1996). The location of these points is constantly varying depending on two factors: the position of the body segments and the breathing phase (inhalation/exhalation).

When the centre of gravity and the centre of volume of displaced water do not coincide, a body at rest in a horizontal position on the water surface undergoes a torque that makes the body turn until the lines of action of the aforementioned forces are in the same vertical line. Generally, this occurs when the body is in a vertical position, and always with the centre of gravity below the centre of flotation. This phenomenon is called super-equilibrium or superstable equilibrium due to the natural tendency of the body to return to this vertical position whenever any external forces act on the body modifying its position.

People with amputated lower limbs are able to float in a horizontal position since the forces of weight and buoyancy are usually applied close together on the body. In the same way, this particular situation is also experienced by people with paralysis in their lower limbs because the amount and density of bone tissue in these subjects is reduced to a minimum.

HYDROSTATIC PRESSURE

Another interesting characteristic that differentiates the aquatic environment from land is the increase in hydrostatic pressure that is experienced inside water. Hydrostatic pressure is directly related to fluid density, and water is 800 times denser than air. As a result, every 10 m of depth in water the hydrostatic pressure increases by approximately 1 atmosphere (101,325 Pa or 760 mm of mercury). It must be taken into account that hydrostatic pressure is exerted equally throughout the surface of the immersed body (Pascal´s law).

Hydrostatic pressure must be seriously considered when diving, especially at great depth, since the increase in pressure compresses the biological tissues and may cause problems in the middle ear if the pressure is not suitably compensated. Soft tissue is most affected by the pressure increase, especially the lungs, whose volume is compressed by half every time the pressure increases by 1 atmosphere. Thus, at 10 m of depth, the lung volume is half of what it was at sea level, and the reduction on lung volume tends to continue in the same line with increasing pressure, although there are internal mechanisms that augment the resistance to compression and therefore the volume does not really decrease in such a mathematical precise way. Even though hydrostatic pressure affects so seriously the human body, the world record for "no limit" free-diving descent (where the diver descends along a guide line aided by a sled with no weight limits and uses an inflatable bag to return to the surface) is 214 m (AIDA, 2013).

Such is the effect of hydrostatic pressure on the body that lung volume and vital capacity decrease significantly just with partial aquatic immersion. When submerged to neck level, the rib and abdominal compression due to hydrostatic pressure causes an increase in the height of the diaphragm and reduces cage circumference by 10% (Agostini, Gutner, Torri, & Rahn, 1966; Chu & Rhodes, 2001). Also, inspiration work increases by 60% (Becker, 2004) and therefore aquatic immersion could be used to strengthen the inspiration muscles (Taylor & Morrison, 1999). This effect has been previously confirmed in patients with spinal cord injury (Pachalski & Mekarski, 1980; Thomaz, Beraldo, Mateus, Horan, & Leal, 2005) and muscular dystrophy (Adams & Chandler, 1974).

The increase in hydrostatic pressure has also been proven beneficial to the cardiovascular system (Christie et al., 1990). The compression experienced when swimming aids venous return and increases stroke volume by an average of 35 % with immersion to neck level (Risch, Koubenec, Gauer, & Lange, 1978; Weston, O´Hare, Evans, & Corral, 1987). This forceful ventricular contraction is known as the Frank-Starling Law, which results in heart rate reductions from 3 to 17 beats/minute (Bates & Hanson, 1996; Goff, Frassetto, & Specht, 1956; Wilder & Brennan, 1993). On the other hand, when the person is on land, the blood from the lower limbs must move upwards against gravity due to the human bipedal position. This situation is aggravated by the inability of the venous return system to pump blood independently. As a consequence, these persistent demands on the cardiovascular system may lead over time to circulation problems such as the formation of varicose veins (Mosti & Partsch, 2012). However, in patients with cardiac or pulmonary pathologies care must be taken, and guidelines for safe immersion of these patients are not currently available (Irion, 2009).

Associated to these cardiovascular responses, the lymphatic system is also affected by aquatic immersion. Greater lymphatic flow has previously been reported (Davis, 2001; Jamison, 2000) and several studies have observed improvements of lymphatic edema on the upper-extremity after breast cancer intervention when patients experienced aquatic immersion (Feightner, 1997; Jamison, 2000; Moseley, Carati, & Piller, 2007).

Hydrostatic pressure also plays a role affecting the neurohormonal and renal systems as well as decreasing pheripheral edema. Firstly, this aquatic pressure leads to an increase in vasopresine and the rennin-angiotensin-aldosterone complex secretion (Farrow et al., 1992; Gerbes et al., 1988). The increased activity of these complexes together with the higher blood flow that occurs during aquatic immersion provokes greater levels of diuresis and, therefore, higher urine production (Buemi et al., 2000). Secondly, hydrostatic pressure has also an important effect on decreasing pheripheral edema. When immersed up to the neck, the pressure at the feet is slightly higher than the diastolic blood pressure, thereby reducing local edema after injury and inflammation (Becker, 2004; Geigle et al., 2001; Jamison, 2000).

Finally, some authors (Becker, 2004; Morris, 1997) indicated that due to the effects of hydrostatic pressure on the human body, the aquatic medium provides an excellent environment to enhance balance and proprioceptive training, especially in early stages of injuries rehabilitation.

THERMOREGULATORY EFFECT

Water immersion is one of the most extended recovery methods (Chulvi-Medrano, Llana-Benlloch, & Pérez-Soriano, 2009). Vaile et al. (2007) suggested that water immersions cause organic alterations and responses that positively influence post-effort recovery. Although there are numerous water recovery methods, Wilcock, Cronin, and Hing (2006) observed that only cryotherapy (water bellow 16ºC) and contrast therapy, consisting in hot (> 36ºC) and cold (< 16ºC) water temperature alternation, are useful as post-effort recovery methods.

Cryotherapy is defined as the curative and recovery method based on the application of cold on a damaged corporal zone (Chulvi-Medrano et al., 2009). The main body responses to cryotherapy include the constriction of peripheral blood vessel which aims to limit heat loss (Guyton, 2006; Srámek, Simecková, Janskỳ, Savlíková, & Vybiral, 2000) and the increase of heat generation that leads to higher secretion of catecholamines and thyroxine (Guyton, 2006; López, 2006). The decrease in body temperature as a consequence of cryotherapy decelerates all chemical and enzymatic reactions (Nelson & Cox, 2013; Zumdahl & Zumdahl, 2008), leading to a reduced muscle tone and pain perception (Cochrane, 2004; Ian M. Wilcock et al., 2006). As a result, the vasoconstrictions produced by the cryotherapy reduces the tissue inflammation and post-exercise edema (Ian M. Wilcock et al., 2006).

The use of contrast therapy is based in the "vaso-pumping" theory (Ian M. Wilcock et al., 2006), which states that changes in temperature increase blood flow, leading to a higher rate of blood lactate reduction after an intense exercise, thereby increasing muscular recovery (French et al., 2008; Vaile et al., 2007).

MUSCULAR ACTIONS

During swimming the body muscles work differently compared to physical activity on land. On land, the body segments undergo regular impact forces every time a foot contacts the ground (walking, jumping, running). In order to carry out any physical activity on land, muscles work firstly eccentrically to slow up the movement, and immediately afterwards they work concentrically, what is called the stretch-shortening cycle (Komi, 1984). During swimming there are no impact forces because of the hydrostatic microgravity, resulting in a minimal participation of the stretch-shortening cycle during aquatic exercise. Thus, it is the concentric muscle actions that predominate when swimming (Miyashita, 1997). Muscles act according to the stretch-shortening cycle only when the person contacts any solid surface, for instance on turns.

Conclusions

It is not easy to find scientific articles that explain the effects of water immersion on the human body. This may be one possible reason why numerous swimming instructors are unable to explain with precision the beneficial effects of aquatic exercise on the human body.

Among all the forces acting on the human body during immersion, the "weight" force is compensated by the buoyancy force and that is the reason why most people float in fresh water. This aquatic floatability together with the hydrostatic pressure occurring during water immersion provides very positive effects on the human body during aquatic exercise resulting in lower joint loading, enhancement of blow flow and lower implication of antigravitatory muscles. Based on this loading reduction, people with articular and circulatory problems and excessive muscular tension may benefit from the effects of aquatic exercise. However, there is still a lack of evidence regarding the effects of aquatic immersion on people with cardiac and pulmonary pathologies, what makes it difficult to make recommendations to these patients.

Regarding the use of water immersion to improve post-exercise recovery, the only two techniques that were demonstrated useful are cryotherapy and contrasts therapy.

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