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“WATER IMMERSED INVERTED PENDULUM”: A PHYSIOMECHANICAL MODEL OF SHALLOW WATER WALKING AT DIFFERENT DEPTHS AND SPEEDS

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Porto Alegre

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Coorientadora: Profa. Dra. Flávia Gomes Martinez

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RESUMO

Durante a caminhada, o corpo humano realiza trocas de energia mecânica como um pêndulo invertido. A cada ciclo de passada é observada essa transformação entre energia cinética horizontal e energia potencial gravitacional do centro de massa. Esse mecanismo de pêndulo invertido atua como uma estratégia de minimização de gasto energético durante a caminhada. Considerando que esse mecanismo é dependente de fatores internos e externos à tarefa de caminhada, e que foi um produto dos agentes de pressão evolutiva em nossa espécie, surge o questionamento sobre o comportamento desse mecanismo de minimização de gasto energético do pêndulo invertido durante condições dinâmicas modernas como a caminhada em água rasa: uma atividade física muito popular e disseminada para um amplo espectro de populações. O objetivo principal desta dissertação foi desenvolver um modelo fisiomecânico do comportamento do pêndulo invertido durante a caminhada em água rasa por homens adultos saudáveis. Nossa hipótese foi que o mecanismo de pêndulo invertido durante a caminhada em água rasa seria afetado pelas forças de empuxo e de arrasto, e que existiria uma profundidade ótima para o custo de transporte mínimo de caminhada devido à interação entre essas duas forças. A dissertação é dividida em quatro seções principais. **1)** Após uma apresentação geral (capítulo 1), nós introduzimos a justificativa para o objetivo principal desta dissertação (capítulo 2) e fornecemos uma base teórica para nosso modelo fisiomecânico do “pêndulo invertido molhado” da caminhada em água rasa (capítulos 3 e 4). **2)** Reportamos uma revisão sistemática (capítulo 5 – estudo 1) de estudos observacionais de variáveis fisiológicas e biomecânicas de caminhada em água rasa em comparação com a caminhada em solo seco. **3)** Com o objetivo de desenvolver um modelo fisiomecânico da caminhada em água rasa, realizamos um estudo experimental (capítulo 6– estudo 2) em que parâmetros fisiológicos, cinéticos e espaço-temporais foram analisados em quatro profundidades (joelho, quadril, umbigo e xifóide) e em cinco velocidades (0,2, 0,4, 0,6, 0,8 m/s e velocidade confortável autosselecionada) durante a caminhada em água rasa por nove homens adultos saudáveis (28 ± 8 anos, 77,7 ± 9,2 kg, 1,78 ± 0,04 m). **4)** Finalmente, as conclusões gerais da dissertação são apresentadas no capítulo 7. O “pêndulo invertido imerso na água” é um modelo fisiomecânico de caminhada em água rasa representado por um diagrama de corpo livre considerando as forças de empuxo e de arrasto atuantes sobre um pêndulo invertido imerso. O resultado principal dessa dissertação é um valor mínimo de custo de transporte na profundidade do quadril apenas na menor velocidade de caminhada analisada (0,2 m/s), em decorrência, provavelmente, de uma relação ótima entre as forças de empuxo e de arrasto nessa condição. Nas velocidades restantes, a profundidade mais econômica de caminhada foi na profundidade do joelho. O gasto energético durante a caminhada em água rasa parece ser influenciado tanto pela profundidade e velocidade de caminhada, o que poderia ser atribuído às forças de empuxo e de arrasto. Futuros estudos testando esse modelo fisiomecânico em outras profundidades, velocidades de caminhada, populações e com um modelo de estimativa da força de arrasto aperfeiçoado são sugeridos.

Palavras-chave: locomoção; caminhada em água rasa; fisiomecânica; imersão em água, otimização.

ABSTRACT

During walking, the human body operates a mechanical energy exchange as an inverted pendulum. At each stride, there is an exchange between the forward kinetic energy and the gravitational potential energy of the center of mass. This inverted pendulum mechanism actuates as an energy saving strategy of walking. Considering that this mechanism is dependent on both intrinsic and extrinsic factors related to walking task and that these factors are product of the evolutionary pressures to our specie, arises the question of the response of the inverted pendulum energy saving during current dynamic conditions as shallow water walking (SWW): a prevalent and disseminate physical exercise to a wide range of populations. The present dissertation's main goal was to propose a physiomechanical model of inverted pendulum response during SWW by healthy adult men. We hypothesized that the inverted pendulum mechanism during SWW would be affected by the buoyancy and drag forces and that would exist an optimal depth for the minimal cost of walking due to the interplay between these forces. The dissertation was divided into four main sections. **1)** After a general presentation (chapter 1), we introduced the dissertation's primary aim justification (chapter 2) and provided a theoretical basis for our "water immersed inverted pendulum" physiomechanical model of SWW (chapters 3 and 4). **2)** We reported a systematic review (chapter 5 - study 1) of observational studies focusing on physiological and biomechanical responses of SWW in comparison to dry land walking.**3)** Aiming to develop a physiomechanical model of SWW, we performed an experimental study (chapter 6 - study 2) where physiologic, kinetic, and spatiotemporal parameters were measured at four depths (knee, hip, umbilical, and xiphoid) and five speeds (0.2, 0.4, 0.6, 0.8 m/s, and at comfortable self-selected speed) during SWW by nine healthy adult men (28 ± 8 years, 77.7 ± 9.2 kg, 1.78 ± 0.04 m). **4)** Finally, we present the dissertation general conclusions in chapter 7. The "water immersed inverted pendulum" is an SWW physiomechanical model represented by a free body diagram that considers both buoyancy and drag forces acting on an immersed inverted pendulum. The main finding was a minimum cost of transport at the hip depth during the slowest walking speed analyzed (0.2 m/s), probably due to the optimal interplay between buoyancy and drag forces at this condition. For the remaining speeds, the most economical depth was at knee. The energy expenditure during SWW seems to be influenced by both depth and walking speed, which could be attributed to buoyancy and drag forces. Future studies testing this physiomechanical model in other depths, speeds, populations, and an improved drag force estimation model are suggested.

Keywords: locomotion; shallow water walking; physiomechanics; water immersion; optimization.

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF TABLES

LIST OF CHARTS

LIST OF ABBREVIATIONS

A: area of body surface
AA: articular angular
Ap: projected frontal area
AP-GRF: anterior-posterior ground reaction force
B: buoyancy force
BF: *biceps femoris*
C: cost of transport
Cd: drag coefficient
CI: confidence interval
D: body diameter.
DLW: dry land walking
DrF: drag force
Ekf: kinetic forward energy
EMG: muscular activity
F: force
Fh and Fh': total forces on the lateral body surfaces
Fr: Froude number
F1: total force in superior body surface
F2: total force on the inferior body surface
g: gravitational acceleration
Gf: gravitational force
GL: *gastrocnemius lateralis*
GlMax: *gluteus maximus*
GlMed: *gluteus medius*
GLMM: Generalized linear mixed model
GRF: ground reaction forces
h: height
HR: heart rate
JM: joint moments
L: body length characteristic
m: rigid body with mass
mV-GRF: mean vertical ground reaction force

m_w: mass of water displaced
NI: not informed
P: pressure
Pg: potential gravitational energy
PMet: metabolic power
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
Psp: *paraspinal*
RA: *rectus abdominalis*
Re: Reynolds number
RPE: rating of perceived exertion
RF: *rectus femoris*
SD: standard deviation
SMD: standard mean difference
SOL: *soleus*
SSWS: comfortable self-selected speed of walking
ST: spatiotemporal
SWW: shallow water walking
TA: *tibialis anterior*
TFL: *tensor fascia latae*
v: velocity;
VL: *vastus lateralis*
VM: *vastus medialis*
VO2: energy expenditure
V-GRF: vertical ground reaction force
y: vertical axis definition
η: fluid viscosity
ρ: specific mass
ρ_f: fluid specific mass
ρ_w: water specific mass

SUMMARY

1. General presentation

This work is part from a research line from the Locomotion research group under coordination from professor Dr. Leonardo Alexandre Peyré-Tartaruga. The main goal from the group is to study energy saving mechanism during human locomotion in different gaits, task conditions, environments, populations. Yet, this study was developed with the co-supervision from Dra. Flávia Gomes Martinez. Her profound knowledge and experience with aquatic physiotherapy were paramount to the study construction in all phases. Besides, the choice to study human walking in shallow water goes along my personal experience with aquatic physiotherapy.

This study has also received important contributions from professor Dr. Alberto Enrico Minetti, helping us to establish the theoretical foundations for the physiomechanical model developed. His analyzes from the data were likewise essential in order to expand our thoughts on the graphic construction and results discussion.

This document has four main sections. 1) We introduced the dissertation's primary aim justification (chapter 2) and provided a theoretical basis for our "water immersed inverted pendulum" physiomechanical model of shallow water walking (SWW) (chapter 3). 2) We reported a systematic review (chapter 5 - study 1) of observational studies focusing on physiological and biomechanical responses of SWW in comparison to dry land walking. 3) Aiming to develop a physiomechanical model of SWW, we performed an experimental study (chapter 6 - study 2). 4) Finally, we present the dissertation general conclusions in chapter 7.

2. Introduction

During walking gait, the human body operates mechanical energy exchange as an inverted pendulum. The body center of mass lays in the upper part of the pendulum, around the hip, and the pendulum pivot is on the floor on the foot. At each stride, it is observed an exchange between the kinetic forward energy and the gravitational potential energy of the center of mass, as these energies fluctuate in phase opposition (CAVAGNA, 2017).

The body center of mass kinetic forward energy is due to the forward velocity from the body displacement; in other words, this kinetic energy is associated to the walking speed. Conversely, the body center of mass potential gravitational energy is due to body weight (gravity acceleration multiplied by the body mass) and the body center of mass vertical position (CAVAGNA, 2017).

In human walking occurs a mechanical energy transference between these energies; one kinetic energy related to the actual movement state, and one potential energy related to the system state characteristics (HALLIDAY; RESNICK; WALKER, 2016). Similar as occurs in a pendular movement - when the kinetic energy is at maximum, the gravitational potential is at minimum - the human body center of mass mechanical response acts as inverted pendulum (Figure 1).

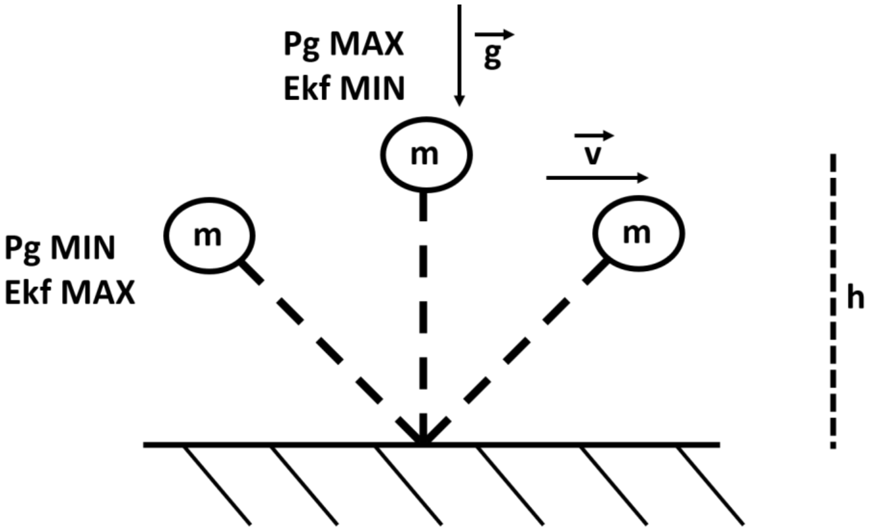


Figure 1 - Inverted pendulum during dry land walking. Ekf: kinetic forward energy; g: gravitational acceleration; h: height; m: rigid body with mass; Pg: potential gravitational energy; v: velocity.

This mechanical energy exchange contributes to reduce energy expenditure during walking; therefore, this inverted pendulum operates as an energy saving mechanism of walking. In order to sustain the dynamic task of walking, the locomotor system has been evolutionary adapted to interchange the mechanical energies associated with locomotion in humans, contributing to reduce the energy expenditure (metabolic energy) necessary to walk (CROMPTON; VEREECKE; THORPE, 2008).

Considering that the inverted pendulum is a mechanical integrative mechanism that helps the organism to save metabolic energy, it can be analyzed by a physiomechanical perspective. Therefore, different mechanical (as external and internal mechanical work, etc.) and physiological (as cost of transport and metabolic power) outcomes can be associated to the inverted pendulum due to the integrative characteristic of this physiomechanical model (CAVAGNA, 2017; PEYRÉ-TARTARUGA; COERTJENS, 2018; SAIBENE; MINETTI, 2003).

Nevertheless, the inverted pendulum mechanism operates optimally in particular dynamic and environmental conditions, being affected by the speed of walking, stride frequency, slope of the terrain, among other factors (CAVAGNA; FRANZETTI, 1986; DI PRAMPERO, 1986; PEYRÉ-TARTARUGA; COERTJENS, 2018). This energy saving mechanism, therefore, is dependent of both intrinsic and extrinsic conditions of the locomotor system. And these optimal dynamical points which the inverted pendulum actuates seems to be evolutionary molded by the natural selection of our species, as the animal body design evolves in direction of the best possible structures and behaviors (ALEXANDER, 1989, 1996).

The inverted pendulum mechanism is an energy saving strategy of the locomotor system of our species – i.e., *Homo Sapiens Sapiens*. Considering that the locomotor system evolved along with all the others organic systems as musculoskeletal, respiratory, postural, neural, cardiovascular (and somehow is an integrative system of all of them), it can be observed that this inverted pendulum mechanism has been under the same biological and evolutionary constraints that our species.

The natural selection that designed *Homo Sapiens Sapiens* along the biological evolution was the same natural selection that designed inverted pendulum. However, to analyze one thing separately from another is a difficult intellectual exercise, considering that this same locomotor energy saving mechanism have been important for our species' evolution (CROMPTON; VEREECKE; THORPE, 2008).

Considering that this inverted pendulum mechanism is dependent from both intrinsic and extrinsic factors related to the walking task, that it has been under the same evolutionary pressure than our species, and analyzing the distinct body activities that we do nowadays in comparison to our early ancestors (LIEBERMAN, 2012), some questions can be raised. We can ask ourself about the response of this ancestral physiomechanical mechanism during the dynamic conditions that we are submitting it now.

One of these modern conditions of physical activity is the aquatic exercise: an exercise option to several healthy conditions and populations with growing utilization in the past years (SO et al., 2018). The physical proprieties from water fluid and its effects on musculoskeletal and physiological systems contribute to this wide application of aquatic exercise. The effects of buoyancy force on weight bearing reduction and drag force on movement resistance are the main water immersion kinetic characteristics that influence the aquatic exercise practice.

Specifically, the shallow water walking (SWW) is a type of aquatic exercise very popular and disseminate to a wide range of populations (LEE; KIM, 2017; STEVENS et al., 2015). The SWW is realized under the effect from buoyancy and drag forces: a distinct environmental physical condition where the human locomotor system have been developed.

In summary, the inverted pendulum mechanism is walking metabolic energy saving mechanism that has been natural selected at the same biological and physical conditions that our species *H. Sapiens Sapiens*, nevertheless today we experience a very distinct life that our early ancestors. Therefore, may the SWW, a popular aquatic physical activity, alters the inverted pendulum mechanism? This is the main question of the present work (DOI: 10.17605/OSF.IO/JFYXN).

2.1 Aims and hypothesis

General aim

To examine the shallow water walking effects on inverted pendulum mechanism through a physiomechanical model from the inverted pendulum response during shallow water walking at different depths (knee, hip, umbilical, and xiphoid) and speeds (0.2, 0.4, 0.6, 0.8 m/s) by healthy adult men.

Specific aims

To perform a systematic review of the literature about physiological, spatiotemporal, kinetic, and muscular activity parameters during shallow water walking;

To analyze the energy expenditure, kinetic and spatiotemporal parameters of shallow water walking at different depths of immersion and speeds of walking by healthy adult men;

To develop a physiomechanical model called “water immersed inverted pendulum” during shallow water walking taking in account the interplay between the buoyancy and drag forces effects.

Hypothesis

Our hypothesis was that the literature systematic review would demonstrate differences of physiological, spatiotemporal, kinetic, and muscular activity parameters between shallow water walking and dry land walking.

We also hypothesized that the different depths of immersion and speeds of walking would affect the energy expenditure, kinetic and spatiotemporal parameters of shallow water walking.

In this sense, our hypothesis was that the inverted pendulum mechanism during shallow water walking would be affected by the buoyancy and drag forces, and that would exist an optimal point of walking cost of transport due to the interplay between these forces.

3. Walking in water: The “water immersed inverted pendulum”

The shallow water walking (SWW) is under the effects from the physical characteristics of the water fluid environment. During dry land walking, the human body is also immersed in a fluid: the air. Nevertheless, when comparing air with water, there are physical differences related to the interaction between the human body and the surrounding fluid.

These differences between fluid-environment are due, mainly, the different specific mass between air and water. The water has a specific mass of about 826 times greater than air (HALLIDAY; RESNICK; WALKER, 2016). This greater specific mass can lead to affect different aspects of SWW physiomechanics.

During SWW, the body moves through the water and is under the effect of principally two forces with higher magnitude in water fluid, than in air fluid. These forces are the buoyancy (B) and drag force (DrF). The former is a hydrostatic force, while the latter is a hydrodynamic force (NUSSENZVEIG, 2002).

The mechanical hydrodynamic and hydrostatic characteristics of aquatic environment will exert influence on the human body while walking at shallow water, and, probably, affects the inverted pendulum mechanism (Figure 2).

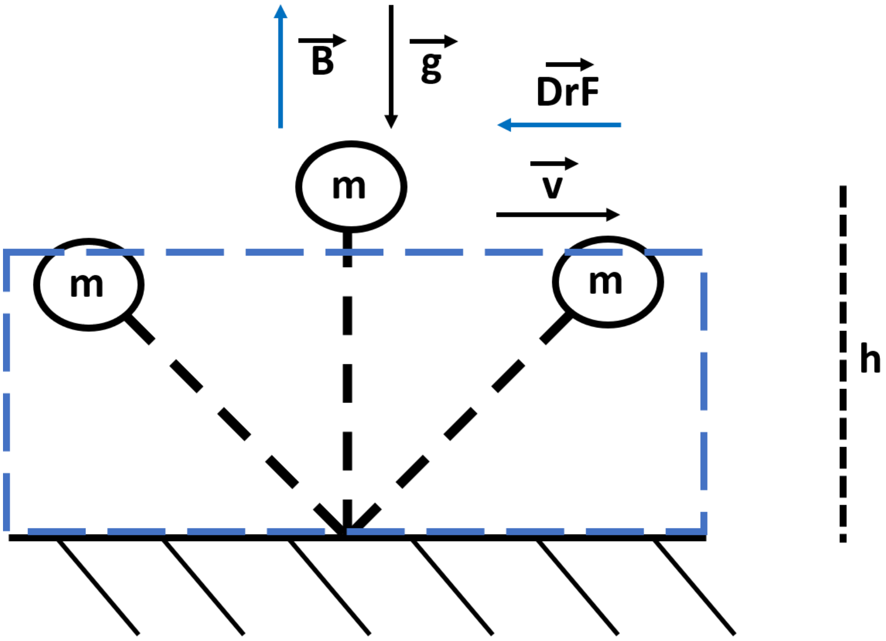


Figure 2 - The inverted pendulum during shallow water walking ("water immersed inverted pendulum"). B: buoyancy force; DrF: drag force; g: gravitational acceleration; h: height; m: rigid body with mass; v: velocity.

In order to better understand the possible effects of the specific physical characteristics of water environment on the inverted pendulum, we first will introduce basic concepts about the physical characteristics of B and DrF. Then, with the purpose to substantiate theoretically the "water immersed inverted pendulum" model, an analytic interpretation from SWW free body diagram (Figure 2) will be performed.

First, the weight reduction effects of B will be approached through the discussion of the literature findings of dry land simulated hypogravity walking. In sequence, due to the lack of specific quantitative data exploring the DrF effects, the effects of DrF resistance on SWW will be discussed inside a systematic review of SWW (Study 1). Finally, the results of the experimental study of SWW in different depths and walking speeds will be presented (Study 2).

3.1 Buoyancy force

The buoyancy force (B) is a hydrostatic force of equal direction and opposite sense than the gravitational force, with a vector pointing up. When a body is immersed in a fluid it suffers simultaneously the B and the gravitational force, the effects of each one diametrically in opposition.

An immersed body is submitted to hydrostatic pressure from the fluid (Figure 3). The hydrostatic pressure is a force applied by the fluid molecules on the immersed body area. According to Stevin law, with higher immersion depth in relation to the fluid surface, higher the hydrostatic pressure. It follows that points equidistant from the fluid surface will suffer equal hydrostatic pressure (NUSSENZVEIG, 2002).

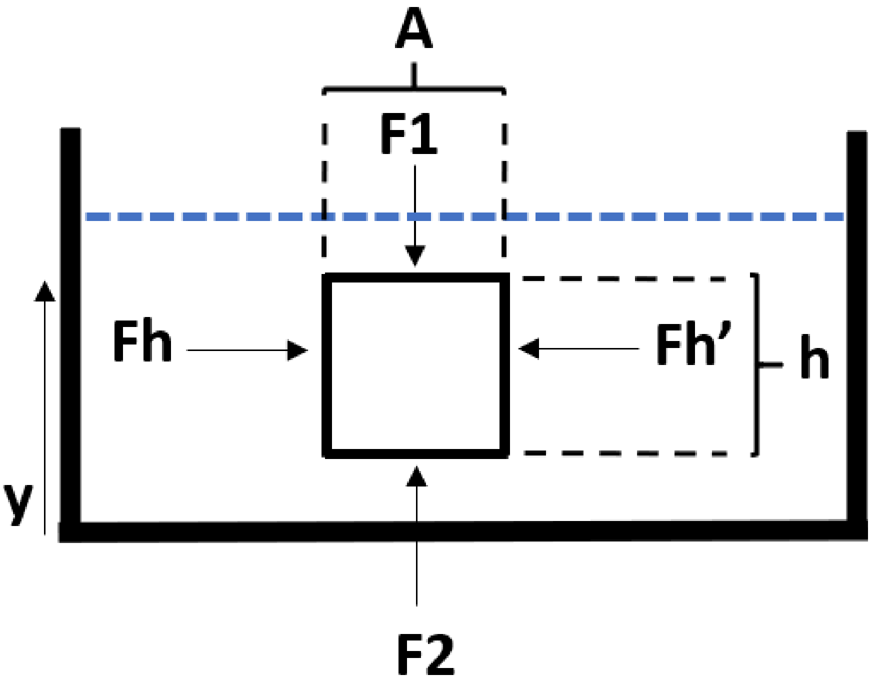


Figure 3 - Hydrostatic pressure of a fluid on a cubical immersed body. A: area of body surface; F1: total force in superior body surface; F2: total force on the inferior body surface; Fh and Fh’: total forces on the lateral body surfaces; h: body height; y: vertical axis definition.

As it is possible to see in Figure 3, the lateral forces Fh and Fh’ - equivalent in magnitude and with opposite sense – cancel each other, considering that these lateral forces are due to hydrostatic pressure. The resultant force from this hydrostatic pressure gradient, thereafter, will be the difference between the forces applied on the superior (F1) and inferior (F2) regions of the immersed body. The resultant force will be on vertical axis pointing up, considering that the hydrostatic pressure on the inferior region will be higher that the hydrostatic pressure on the superior region (F2 > F1). This resultant force is called B (Figure 4 and Equation 1), defined by Arquimedes’ principle, and has same magnitude than the weight from the volume of fluid displaced by the immersed body (NUSSENZVEIG, 2002).

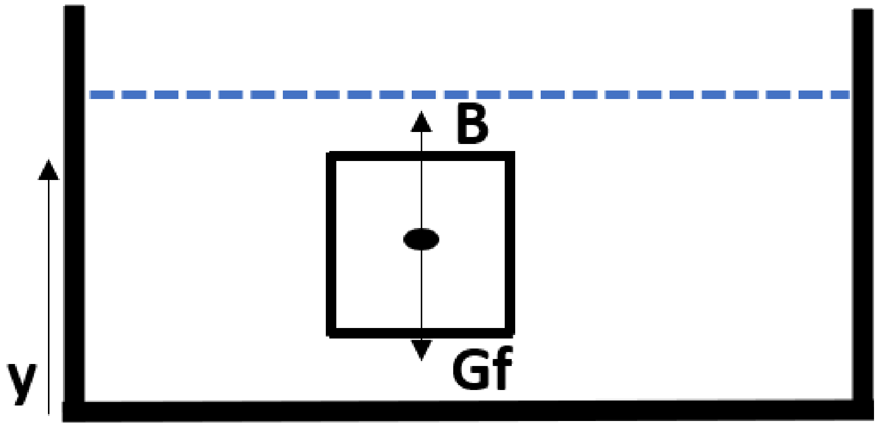


Figure 4 - Buoyancy and gravitational forces applied on an immersed body. B: buoyancy force; Gf: gravitational force; y: vertical axis definition.

The B effects oppose those of gravitational force, reducing the apparent weight from an immersed body. The apparent weight is the subtraction of B from the real body weight (body mass times gravitational acceleration). In summary, higher the body volume fraction immersed, higher the fluid volume displaced, higher B magnitude, lower the body apparent weight (HALLIDAY; RESNICK; WALKER, 2016).

Equation 1 - Buoyancy force.

$$B = m_w \, . \, g$$

where, B: buoyancy force; m_w: water mass; g: gravitational acceleration.

Equation 1 development

By Stevin law

$$P2 = P1 + \rho_w \, . \, g \, . \, h$$

where, $P2$: hydrostatic pressure at deeper point 2; $P1$: hydrostatic pressure at shallower point 1; ρ_w: water specific mass. g: gravitational acceleration; h: body height.

$$P2 - P1 \; = \rho_w \, . \, g . \, h$$

Therefore, the resultant force from the superficial forces applied on an immersed body will be a vertical B force (Arquimedes' principle).

With,

$$P = \frac{F}{A}$$

where, P: pressure; F: force; A: area of body surface

$$B = \; P2 \, . \, A - P1 \, . \, A$$

Then,

$$B = \; \rho_w \, . \, h \, . \, A \, . \, g$$

With volume definition,

$$B = \; \rho_w \, . \, V . \, g$$

where, V: body volume.

So,

$$B = \; m_w . \, g$$

As we wanted to demonstrate.

The application of these kinetic concepts to the human body immersed at shallow water is evident. At a deeper immersion depth, a greater water volume will be displaced, a greater B the human body will experience, and a lower apparent body weight will occur. A summary of the apparent body weight in percentage of the real body weight at different immersion depths in relation to anatomical landmarks from different studies is presented in Chart 1. Considering that different authors have analyzed different immersion depths, more than one study was used to organize this chart in order to provide a more comprehensive view of the B effect on the apparent body weight reduction in several depths of immersion.

Chart 1 - Apparent body weight at different immersion depths in relation to anatomical landmarks.

Immersion depth	**Apparent body weight (% of real body weight)**
C7	8% (HARRISON & BULSTRODE, 1987)
Axillar	20% (MIYOSHI et al., 2004)
Xiphoid	43% (MACDERMID, FINK, STANNARD, 2017), 35% (HARRISON & BULSTRODE, 1987) 34,7% (ORSELLI; DUARTE, 2011),
Anterior superior iliac spine	54% (HARRISON & BULSTRODE, 1987) 52,3% (ADEGOKE et al., 2014)
Thigh	74% (MACDERMID, FINK, STANNARD, 2017)

Sources: ADEGOKE et al., 2014; HARRISON & BULSTRODE, 1987; MACDERMID, FINK, STANNARD, 2017; MIYOSHI et al., 2004; ORSELLI; DUARTE, 2011.

3.2 Drag force

The drag force (DrF) is a hydrodynamic force with same direction and opposite sense to the velocity vector of the immersed body, with a vector in opposite sense to the displacement of the immersed body. Its application on the body, therefore, generate a tendency to reduce the linear moment of the body. In conclusion, DrF is a resistance force to the immersed body (FOX; MCDONALD; MITCHELL, 2018).

The total DrF can be divided into three components: wave DrF, frictional DrF, and pressure (shape) DrF (Equation 2) (TOUSSAINT; STRALEN; STEVENS, 2002). The wave DrF is due to the water surface deformation during displacements at the interface between water and air. The frictional DrF is due to the fluid viscosity, effect from the friction between the body surface and the fluid layers. The pressure DrF is due to the pressure forces applied on the body surface and is related to the body shape (FOX; MCDONALD; MITCHELL, 2018; NUSSENZVEIG, 2002; TOUSSAINT; BEEK, 1992).

Equation 2 - Components of total drag force.

$$DrF\ total = DrF\ wave + DrF\ frictional + DrF\ pressure$$

where, DrF: drag force.

The wave DrF is present during body displacements on the water surface, since that at this condition the body speed is restricted by the wave formation. With the increase of the body speed, the wave formation increases, raising the movement resistance as a result from the wave DrF. An important parameter for the wave DrF is the hull speed: a critical speed for the body displacement on the fluid surface. When the body in movement approaches the hull speed, it undergoes a higher wave DrF resistance, because the waves formed in its front do not have enough time to flow away, generating a higher resistance. This greater resistance, ultimately, limits the body speed increase (AIGELDINGER; FISH, 1995).

The hull speed is dependent from the waterline length; that is, the longitudinal length of the body lying on the fluid surface measured along the direction of the body velocity vector. Bodies with greater waterline length have greater hull speed, and, therefore, will encounter a larger wave DrF only at higher absolute speeds of displacement in comparison to bodies with smaller waterline length (AIGELDINGER; FISH, 1995).

Toussaint et al. (2002) have reported a contribution of 12.1% of wave DrF to total DrF during crawl swimming at 1.89 m/s. The authors estimate that for a subject with 2.0 m stature, the hull speed will be 1.77 m/s; thus, the analyzed swimmers were capable to swim at speeds higher than the hull speed. We do not have found, however, studies analyzing the wave DrF during shallow water walking (SWW).

During SWW the body is at vertical position, while in swimming the body is at horizontal position. The waterline length is lower at SWW in comparison to swimming. One could assume, in this sense, that the hull speed will be lower during SWW than swimming (1.89 m/s). And, consequently, the relative greater contribution of wave DrF to total DrF will be reached at slower speeds during SWW than at swimming.

The relation between the relative contribution of frictional and pressure DrF to total DrF can be understand by the ratio between these two forces through the Reynolds number (Re). The Re (Equation 3) is a dimensionless ratio between pressure and frictional forces; higher Re number means a greater pressure force magnitude in relation to frictional forces. Also, at lower Re the predominant flow is laminar, while at higher Re the predominant flow is turbulent (FOX; MCDONALD; MITCHELL, 2018).

Equation 3 - Reynolds number (Re).

$$Re = \frac{v.D.\rho_f}{\eta}$$

where, Re: Reynolds number; v: velocity; D: linear dimension; ρ_f: fluid specific mass; η:fluid viscosity.

The relation between pressure DrF and frictional DrF is determined by the boundary layer concept. The boundary layer is a fluid region closer to the body surface, and only in this region the frictional viscous forces are important. In the more internal region of this boundary layer - in other words, at fluid surface in direct contact with the body – the flow speed is null. This speed gradient between the fluid layers in consequence of the boundary layer is the origin of resistance by frictional forces (frictional DrF) (FOX; MCDONALD; MITCHELL, 2018).

At higher flow speeds, with greater Re, occurs the wake phenomenon due to turbulent flow (Figure 5). During the fluid flow on an immersed body surface, the fluid particles suffer a deacceleration in consequence from viscosity. At greater flow speed (turbulent flow) the fluid yet suffers the deacceleration due to the negative pressure gradient (wake) on the posterior body region. This fluid deacceleration due to friction and pressure gradient is so important, that the fluid particles reduce their speed until rest on the posterior body region (FOX; MCDONALD; MITCHELL, 2018).

These fluid particles that reduce their speed until rest at the body posterior region suffer a phenomenon of flow separation. In this condition, the boundary layer detach from the body surface at the point of separation, creating a low-pressure wake region. These particles that detach are moved away by the next particles. With this low-pressure wake region occurs an increase of the DrF, because, further on the high positive pressure on the anterior body region, this low-pressure wake region contributes to exacerbate the DrF. The DrF therefore, is a force that resists the body displacement through a fluid, creating the tendency to deaccelerate the body (FOX; MCDONALD; MITCHELL, 2018)

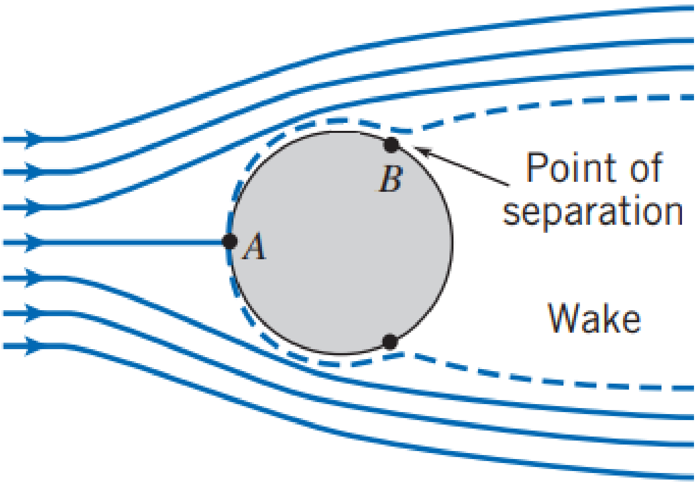


Figure 5 - Fluid flow on an immersed body at higher Reynold number creating a low-pressure wake region. A: high pressure point. B: point of separation of boundary layer. Figure extracted and adapted from Fox, McDonald, Mitchell (2018).

For SWW, Newman (1992) reported Re values between 0.82 x 10^5 and 6.88 x 10^5 at a walking speed of 1.5 m/s, suggesting the predominance of turbulent flow during SWW. The pressure DrF (Equation 4), thereafter, contribute predominantly to total DrF during SWW. For the DrF analysis during SWW in the present study, we used a mathematical model proposed by Orselli & Duarte (2011) to estimate the DrF during the stride cycle; in detail, this model takes in account only the pressure DrF.

Equation 4 - Pressure drag force.

$$Pressure\ DrF = \frac{1}{2} \, . Cd \, . \rho_f \, . Ap \, . v^2$$

where, DrF: drag force; Cd: drag coefficient; ρ_f: fluid specific mass; Ap: projected frontal area; v: velocity.

4. Hypogravity walking

The walking in hypogravity is the walking performed in conditions where the vertical downward gravitational force effects are diminished in relation to Earth normogravity. The hypogravity is the condition where the gravitational acceleration is lower than from the Earth gravitational acceleration of 1.0 g (or 9.81 m/s^2) (LACQUANITI et al., 2017). There is a growing interest on the hypogravity locomotor physiomechanics due the human space exploration (CAVAGNA; WILLEMS; HEGLUND, 1998; PAVEI; MINETTI, 2016) and advantages of reduced weight bearing walking in different clinical conditions (HUBLIE & DIETZ, 2013; SALE et al., 2012). Yet, different walking physiomechanics is both expected theoretically (MARGARIA; CAVAGNA, 1964) and observed experimentally (LACQUANITI et al., 2017; SYLOS-LABINI; LACQUANITI; IVANENKO, 2014) during simulated hypogravity in comparison to normal gravity conditions.

Gravity exerts a great influence on dry land walking, determining the inverted pendulum mechanism for energy recovery during the walking stride cycles (CAVAGNA; WILLEMS; HEGLUND, 1998, 2000; SYLOS-LABINI; LACQUANITI; IVANENKO, 2014). At each stride, the locomotor system takes advantage of the gravity downward force to fall forward and convert the body center of mass potential gravitational energy (height-dependent) into kinetic energy (speed-dependent), and latter this kinetic energy is used to restore the body center of mass height again (CAVAGNA; WILLEMS; HEGLUND, 1998). The gravitational force importance to this mechanical energy saving mechanism can be observed due to its relation with the potential gravitational energy.

One important concept to discuss about hypogravity locomotion is the principle of dynamic similarity. The dynamic similarity in locomotion states that dynamically similar bodies will behave similar – i.e., will have similar gait pattern – if their dynamic characteristics are similar. The principle of dynamic similarity allows the comparison of different bodies at similar movement conditions, and enables to compare the same body at different movement conditions. An important dynamic similarity parameter to analyze movements that are affected by gravitational force is the Froude number (ALEXANDER, 1989; LACQUANITI et al., 2017).

The Froude number (Equation 5) is a dimensionless unit that express the ratio between kinetic energy and potential gravitational energy. The higher the speed of locomotion, higher kinetic energy associated to the movement. The higher the gravitational acceleration, higher the potential gravitational energy associated to the movement. The L factor corresponds to a geometric characteristic from the body length (ALEXANDER, 1989; LACQUANITI et al., 2017).

Equation 5 - Froude number (*Fr*). *v*: velocity; *g*: gravitational acceleration; *L*: body length characteristic.

$$Fr = \frac{v^2}{g.L}$$

Where, Fr: Froude number; v: velocity; g: gravitational acceleration; L: body length characteristic.

The Froude number can also be associated to a ratio between centrifugal (mv^2/L) and centripetal (mg) forces. In this sense, while the centripetal force is higher than centrifugal (Froude number < 1), the body can maintain walking gait without an aerial phase. But when the centrifugal force overcomes the centripetal (Froude number > 1), an aerial phase occurs, the walking gait becomes impossible, and running is the gait adopted (LACQUANITI et al., 2017). Experimentally, however, it has been observed that the walking-running transition in normal gravity condition occurs at 0.5 Froude number (IVANENKO et al., 2011; KRAM; DOMINGO; FERRIS, 1997). At simulated hypogravity, the walking-running transition occurs at a Froude number about 0.5, but at slower absolute speed than normal gravity condition (IVANENKO et al., 2011; KRAM; DOMINGO; FERRIS, 1997); this phenomenon is well exposed by Sylos-Labini et al. (2014), so here we reproduce their figure (Figure 6).

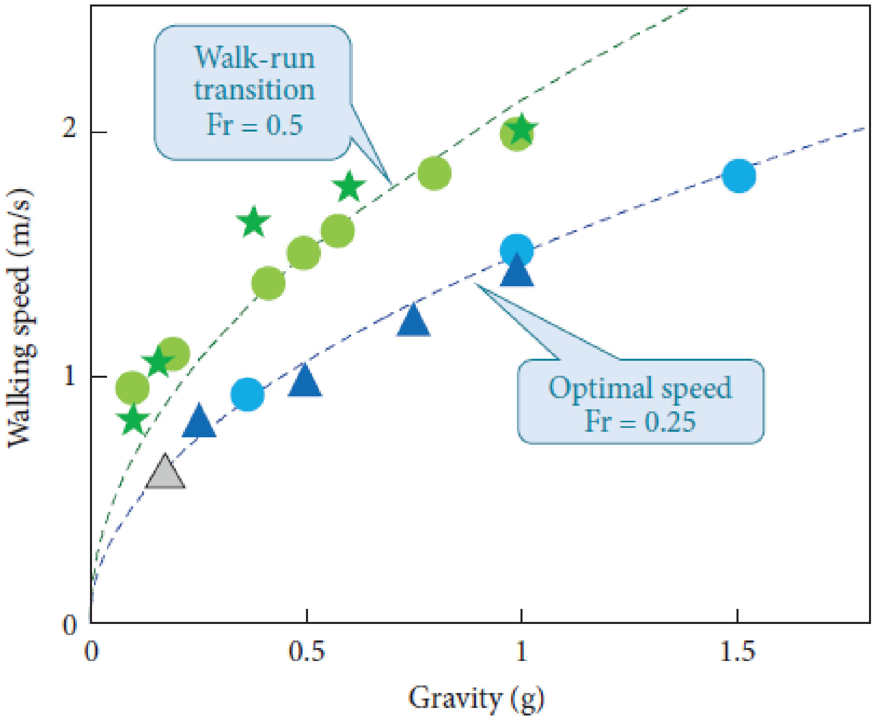


Figure 6 - Walking-running transition and optimal walking speeds at different gravity conditions. Fr: Froude number. Each type symbol represents one study different. Blue circle: Cavagna, Willems and Heglund (1998, 2000); blue triangle: Griffin, Tolani and Kram (1999); green circle: Kram, Domingo and Ferris (1997); green star: Ivanenko et al. (2011); grey triangle: Margaria and Cavagna (1964). Figure extracted and adapted from Sylos-Labini, Lacquaniti and Ivanenko (2014).

Lower gravity conditions cause the locomotor functional repercussion of a walking speeds range narrowing. In consequence from reduced gravity, there is a reduction of the potential gravitational energy available to be converted into kinetic forward energy through pendular mechanism. Therefore, the maximum speed that the locomotor system can sustain walking gait type is diminished at simulated hypogravity, reducing the range of walking speeds (CAVAGNA; WILLEMS; HEGLUND, 2000; MARGARIA, CAVAGNA, 1964).

Also, accordingly to the principle of dynamic similarity, the simulated hypogravity affects not only the walking-running transition speed, but the optimal speed of walking as well. The optimal speed of walking is the speed which the exchange between potential gravitational energy and kinetic energy is optimized; in other words, the speed which the recovery is maximum (CAVAGNA; THYS; ZAMBONI, 1976; CAVAGNA; WILLEMS; HEGLUND, 2000). Considering that the self-selected speed (SSWS) of walking is close to the optimal speed (SAIBENE; MINETTI, 2003), Salisbury et al. (2015) have found lower SSWS at simulated hypogravity conditions (0.38 and 0.16 g) in comparison to normal gravity (1.0 g).

During simulated hypogravity walking, the maximum recovery occurs at lower walking speeds than at Earth gravity, and at an even walking speed the recovery is lower at simulated hypogravity (CAVAGNA; WILLEMS; HEGLUND, 1998, 2000; GRIFFIN; TOLANI; KRAM, 1999; PAVEI; BIANCARDI; MINETTI, 2015). This recovery response modification in relation to absolute walking speed during simulated hypogravity indicates an alteration from the inverted pendulum mechanism in conditions where the gravitational acceleration is reduced. Nevertheless, when adjusted for the gravity acceleration of each condition, Pavei, Biancardi & Minetti (2015) observed that the maximal recovery was reached at similar Fr number (0.22 to 0.26) comparing Earth (1.0 g), Mars (0.36 g), and Moon (0.16 g) gravities.

In relation to the mechanical work of walking, Cavagna, Willems and Heglund (2000) (1.5, 1.0, 0.4 g), Griffin, Tolani and Kram (1999) (1.0, 0.75, 0.5, 0.25 g), and Pavei, Biancardi and Minetti (2015) (1.0, 0.36, 0.16 g), reported lower external mechanical work with lower gravity at even walking speeds. This reduced external mechanical work seems to be related to the reduced magnitude fluctuations from the potential gravitational and kinetic forward energies curves during walking at simulated hypogravity (CAVAGNA; WILLEMS; HEGLUND, 2000; GRIFFIN; TOLANI; KRAM, 1999; MARGARIA; CAVAGNA, 1964; PAVEI, BIANCARDI, MINETTI, 2015)

The authors (CAVAGNA, WILLEMS, HEGLUND, 2000) yet discuss that the internal mechanical work seems to be independent from gravity or to decrease with it, considering that the stride frequency is about the same or decreases at lower gravity conditions. While Pavei, Biancardi and Minetti (2015) observed a diminished internal work at simulated hypogravity, but with no differences between the simulated hypogravity conditions (0.36 vs. 0.16 g). In this way, the total mechanical work during walking - the sum of external and internal - will be lower at lower gravity (CAVAGNA; WILLEMS; HEGLUND, 2000; PAVEI; BIANCARDI; MINETTI, 2015).

About the ground reaction forces, Newman and Alexander (1993) and Newman, Alexander and Webbon (1994) observed a reduced peak ground reaction force values with the decrease in gravity level (1.0, 0.9, 0.67, 0.38, 0.17 g). Richter et al. (2017) performed a systematic review with meta-analysis from 43 studies including several biomechanical and physiological parameters of simulated hypogravity locomotion, and they have observed along with the gravity acceleration reduction a systematic reduction from body weight, ground reaction forces peak, rate of force development, and impact forces.

Comparing the spatiotemporal parameters during walking at simulated hypogravity, Griffin, Tolani and Kram (1999) and Pavei, Biancardi and Minetti (2015) do not have found difference of stride frequency with reduction of gravity at even speed, while Cavagna, Willems and Heglund (2000) reported a similar or reduced stride frequency at lower gravity during walking at even speed. Newman & Alexander (1993) and Newman, Alexander and Webbon (1994) also described lower stride frequency and lower duty factor with lower gravity. The stride frequency results discrepancies during simulated hypogravity walking between these studies could be related to the weight reduction apparatus adopted by the authors, as Sylos-Labini et al. (2013) already have demonstrated gait kinematic alterations due to the gravity reduction simulator chosen. Namely, Griffin, Tolani and Kram (1999) and Pavei, Biancardi and Minetti (2015) used trunk suspension device; Cavagna, Willems and Heglund (2000) collected data during a parabolic flight; Newman and Alexander (1993) and Newman, Alexander and Webbon (1994) employed underwater treadmill.

What concern the cost of transport (C) at simulated hypogravity conditions, there seems to be an imbalance between the external mechanical work reduction and the C reduction at simulated hypogravity (GRIFFIN; TOLANI; KRAM, 1999). With the gravity level reduction occurs both a reduction of external mechanical work and C, although the reduction of external mechanical work is more accentuated than that of C.

Griffin, Tolani and Kram (1999) observed a reduction of 50% from the external mechanical work, while the C reduced only 25% when the gravity was reduced by half (1.0 vs. 0.5 g). Walking in simulated hypogravity appears to be a locomotion type of relatively high C when normalized by the apparent body weight; in other words, comparing even walking speed, the mechanical work curve suffers a steeper decay with gravity reduction than C curve. The authors discuss that this uneven reduction of external mechanical work and C could be related to fact that not only the external work is a source of energy expenditure. But the work necessary to move the limbs – internal mechanical work – should also be taken in account (CAVAGNA; WILLEMS; HEGLUND, 2000; GRIFFIN; TOLANI; KRAM, 1999).

Pavei, Biancardi and Minetti (2015) have analyzed the C and both external an internal mechanical work during walking at even speeds in simulated hypogravity. In spite of the reduced external and internal mechanical work at lower gravity levels (0.36 and 0.16 g) in comparison to Earth gravity (1.0 g), the authors did not found a statistically significant C reduction during simulated hypogravity walking. The differences between the results of this study with others from the literature that show the C reduction in simulated hypogravity - as Farley & McMahon (1992) – can be related to the setup apparatus to simulate simulated hypogravity.

About the relation of C with speed of walking, Pavei, Biancardi and Minetti (2015) also reported the maintenance of the U-shaped curve of C at simulated hypogravity conditions. The authors yet found that a minimum point of C was reached at similar speeds of walking in all gravity conditions (1.0, 0.36, and 0.16 g). This behavior of C curve - taken in conjunction with the mechanical recovery features at reduced gravity stated above - suggests that the inverted pendulum mechanism seems to operate also at dry land simulated hypogravity walking.

In conclusion, we can observe that the gravity acceleration reduction affects different aspects from the physiomechanics of dry land simulated hypogravity walking, with the mechanical perspective contributing to understand the narrower range of walking speeds during dry land simulated hypogravity. And as it can be seen by the recovery and C responses, in spite of the center of mass mechanical energies alterations reported during simulated hypogravity, the inverted pendulum mechanism appears to have a somewhat important function during dry land simulated hypogravity walking.

4.1 Bridge between dry land simulated hypogravity and shallow water walking

We can observe that the human walking is affected in different physiomechanical ways by the gravity acceleration reduction. The mechanical energies response, the energies exchange, the spatiotemporal parameters, the cost of transport: all these variables seem to be altered during dry land simulated hypogravity walking.

The dry land simulated hypogravity walking discussion comes to us an argumentative resource to substantiate the weight bearing reduction effects that the water exerts on the “water immersed inverted pendulum”. But during the immersion in water, the “water immersed inverted pendulum” is not only under the effects of a gravitational acceleration attenuate force (buoyancy) but is also suffering the effects of a movement resistance force (drag force).

Considering the individual effect of the gravity reduction on human walking physiomechanics, we can move forward in our exploration in order to analyze the effects of shallow water immersion on this “water immersed inverted pendulum”. So far, we have discussed the vertical axis of the “water immersed inverted pendulum” free body diagram, considering the consequences of simulated hypogravity. But now we propose the addition of the horizontal kinetic axis to our free body diagram; that is, consider also the dynamic drag force resistance effects on the “water immersed inverted pendulum”.

However, before enter into the exploration of the experimental data concerning the effects of depth and speed of walking on the physiomechanics of shallow water walking (Chapter 6: Study 2), the very next chapter will bring the Study 1 (Chapter 5): a systematic review from the literature on shallow water walking and their physiological, spatiotemporal, kinetic, and muscular activity parameters.

If until this point we have discussed the dry land simulated hypogravity walking, now we begin the specifically analyze simulated hypogravity walking during water immersion.

5. Study 1: Quantifying the acute responses of shallow water immersion on walking physiology and biomechanics: a systematic review and meta-analysis

Abstract

Shallow water walking (SWW) generates changes in cardiorespiratory parameters in comparison to terrestrial exercise, and these changes are highly dependent of immersion depth. We reviewed the evidence from observational studies focusing on physiological and biomechanical responses of SWW in comparison to dry land walking. This systematic review and meta-analysis (initial search: 1516 studies; systematic review: 40 studies; meta-analysis: 22 studies) presents evidence that higher energy expenditure, heart rate and rating of perceived exertion are accompanied by depth-dependent reductions in self-selected speed and stride length in SWW compared with dry land. The stride frequency, however, was similar at waist and reduced at xiphoid depth. As expected, the ground reaction forces were reduced according to the buoyance forces acting. SWW appears to increase muscular activity. Importantly, the depth-related increase in energy expenditure of SWW seems to involve a major role of resistive forces compensating the reduced task of support the body weight. Besides the benefits of water immersion as reduced joint impact, biomechanical alterations on force production may produce additional long-term gains in functional mobility. However, the influence of these physiological and biomechanical alterations on functional mobility are largely unknown. Due to these inconclusive points, there is a huge opportunity to determine (1) the alterations on muscle activation in different depths in order to explain the higher energy expenditure at organismal level, and (2) whether these alterations can maximize gains in metabolic economy and gait biomechanics after long-term SWW intervention. PROSPERO registration protocol: CRD42018113040.

Keywords: head-out aquatic immersion; locomotion; metabolic cost; aquatic exercise; biomechanics

5.1 Introduction

Exercise in aquatic environment is a feasible and recommended intervention to a wide range of populations. The practice of physical exercise in water is advantageous to a variety of health conditions, having benefits in pain (5, 22, 60, 63), muscle strength (7, 8, 72, 74), mobility (22), equilibrium (75), flexibility (7, 72), cardiorespiratory capacity (72), functionality (7, 63, 74, 75). The benefits from the aquatic exercise intervention can be associated with the physical characteristics of this environment. In this way, the shallow water walking (SWW) is a popular method of water immersion exercise (43, 68).

The locomotion is dependent from environment and task constraints (12, 19, 59). While, in water immersion, the relative high density induces the addition of two forces neglected in dry land walking (DLW): drag and buoyancy forces (19). The drag force (DrF) is a force that resists to the displacement of a body immersed in a fluid. The drag force magnitude is directly dependent to the density of the fluid, the cross-sectional area of the moving body, a fluid drag coefficient, and the square of the relative velocity of the body in relation to the fluid (19). Therefore, the higher water density generates a higher DrF at a given walking velocity in aquatic environment in comparison with land. The buoyancy force (B) is the vertical force in opposite direction to the gravitational force, resulting from the difference in the gradient of hydrostatic pressure applied to the immersed body, and is directly dependent of the displaced fluid mass (55). Accordingly, greater the immersion depth, greater body volume immersed, greater the B, and smaller the apparent body weight to be supported and propelled by the locomotor system.

In comparison to DLW, SSW presents altered physiological and biomechanical parameters such as increased energy expenditure and heart rate (HR) (27), and reduced range of motion (ROM) and kinetic parameters (4). Heywood et al. (33) developed a systematic review comparing gait parameters in water and dry land. Their search comprised spatiotemporal, kinematic, kinetic, and muscular activity parameters. Despite the many variables analyzed, a meta-analytic approach to examine changes in metabolic economy of SWW is lacking (19). Also, the role from depth immersion on physiological and biomechanical parameters is unknown. Furthermore, the findings on energy expenditure parameters are controversial in previous studies. Some studies have found that water immersion produces higher (2, 6, 30) values and others have found similar (2, 30, 70) values of energy expenditure in shallow water in comparison to dry land.

Therefore, this review 1) systematically appraised the available evidence from observational studies, analyzing the physiological and biomechanical responses of SSW in comparison to DLW and testing the influence of immersion depth in healthy adults and elderly; 2) meta-analytically pooled physiological and biomechanical measurements comparing the SWW and DLW responses; and 3) provides scoping lines for future research to enhance the understanding of potential gain from SWW in the health context.

5.2 Methods

This systematic review was registered as protocol at PROSPERO (registry number CRD42018113040) (Annex 1) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist was followed to conduct and to report this study.

Data extraction and quality assessment

The search strategy was elaborated accordingly to the PICOT strategy. Combinations from the subsequent terms were used: “walk”, “gait”, “shallow water”. The search was conducted at November of 2018 and actualized at September of 2019 in PubMed Medline, Cochrane, Scopus, and Embase databases, including studies from inception until the search date (Appendix 1). Handsearching was also performed by the reference lists of obtained articles at the digital databases.

Eligibility criteria

The studies included in this systematic review were selected based on the subsequent inclusion criteria: i) Participants: healthy adults and/or elderly; ii) Experimental condition: walking in shallow water at any depth. Studies that evaluated walk in dry land were also included only if them have evaluated walking in shallow water as well; iii) Outcomes variables analyzed: spatiotemporal, articular range of motion, ground reaction forces, muscle activity, physiologic parameters; iv) Study design: observational or experimental; v) Publication in peer-reviewed journal in English, Portuguese or Spanish language.

Selection of studies

After the search in databases, two reviewers (A.I-M and M.Z.C) selected independently the studies in the following steps: 1) Screening: the studies found in the databases were first selected accordingly the inclusion criteria by title and abstract, also the duplicates were excluded. 2) Eligibility: the studies remaining from step 1 were evaluated accordingly the inclusion criteria by their full text reading. 3) Inclusion in the systematic review: the studies remaining from step 3 were considered included in the systematic review. 4) Inclusion in the meta-analysis: the meta-analysis was performed for a specific variable when a sufficient number of studies using the same unit of measure compared the variable in different depths in similar experimental conditions (speed of walking, for example). In case of disagreement between different views a third author (R.R.C) was consulted.

Data extraction and quality assessment

The extraction of data from the studies included in the systematic review was made independently by two reviewers (A.I-M and M.Z.C). The data extracted of each included study was the following: authors, year of publication, number of participants, age from the participants, depth of immersion, water temperature, local of walking (floor or treadmill), speed control method, speed of walking, and physiological, spatiotemporal, angular, kinetic, and neuromuscular parameters. In case of missing data, a written solicitation was sent by e-mail to the authors of the article.

The data extracted for each parameter were: 1) Physiological: energy expenditure, HR, rating of perceived exertion (RPE). 2) Spatiotemporal: speed, stride frequency, stride length, stride duration, duty factor. 3) Angular: articular ROM. 4) Kinetic: ground reaction forces, joint moments. 5) Neuromuscular: electromyographic activity (EMG).

The quality assessment of the included studies was performed with a checklist based on Downs and Black (21). There was a total of 8 questions to be analyzed. The questions are described in Table 2. Each question was rated as 2 (satisfying description), 1 (limited details), or 0 (no information). The methodological quality of the studies was rated according to criteria proposed by Hootman et al. (35) in percentage of the total possible score achieved by the study as: low (≤33%), moderate (33.4% to 66.7%), and high (≥66.8%).

Data analysis

A meta-analysis was conducted. The comparisons were performed between land and one specific immersion depth. The depths selected were those with sufficient available data to perform meta-analysis. The mean and standard deviation values of physiological, spatiotemporal, angular, and kinetic parameters were used. Results are presented as standardized mean differences. Both fixed and random effect models were used. The inconsistency was evaluated using the I^2 test, and heterogeneity level was evaluated accordingly to Higgins et al. (34). Forest plots were generated to present the pooled effect and the standardized mean differences (SMD) with 95% confidence intervals (CI). The statistical significance level was $\alpha = 0.05$. The analyzes were conducted using in RStudio (1.3.1056, PBC, Boston, USA).

To perform the meta-analysis of energy expenditure, some considerations must be pointed out. Firstly, the meta-analysis was realized for studies that compared the same depth conditions. Secondly, only studies that analyzed the same walking speed in both depth conditions were included in the meta-analysis. Lastly, due to the different units used by the studies to report energy expenditure, we performed data unit adjustments.

These data unit adjustments were made to facilitate the comparison between the studies and to express the energy expenditure in Joules (J), accordingly to the International Unit System. Also, we calculate the energy expenditure normalized in the space domain. The meta-analysis of energy expenditure therefore was performed for both the units of J/kg/min (PMet) and J/kg/m (C) (59). It is worth noting that the C is calculated from the gross oxygen consumption values given by the studies, considering that only one study (16) informed energy expenditure in net oxygen consumption, but this study was not included in the meta-analysis because evaluated an incremental submaximal test.

5.3 Results

Studies selection

The initial search at databases resulted in 1516 studies, of which 196 duplicates were excluded (Figure 7). After title and abstract screening, 64 studies remained for the full text reading assessment. Of these, 34 studies were included; and 6 more additional studies from the reference lists of the included studies were selected. Therefore, a total of 40 (2–4, 6, 10, 11, 15–17, 20, 23, 24, 26–28, 30, 31, 36–40, 42, 44, 46–49, 51–54, 56, 61, 62, 65–67, 70, 73) studies were included in this systematic review.

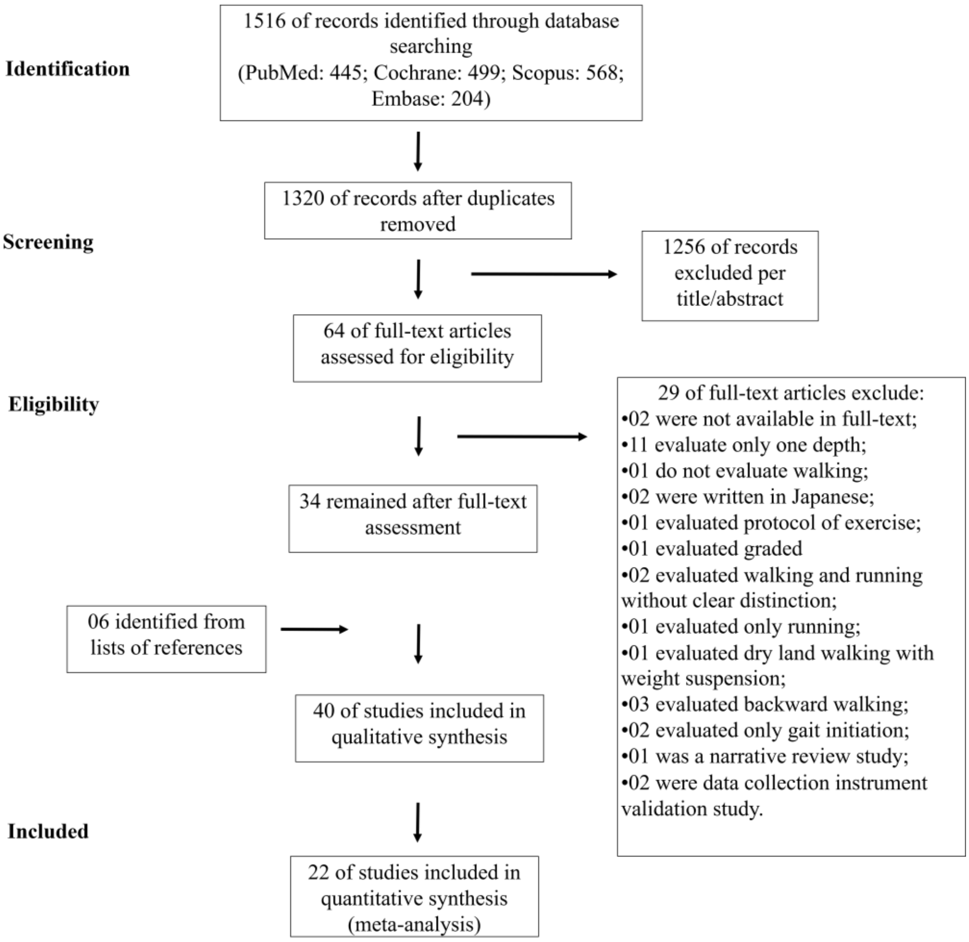


Figure 7 - Flow chart of studies research and selection for inclusion.

Characteristics of included studies

All data are available at supplementary material (DOI: 10.6084/m9.figshare.13225304). The studies characteristics are summarized in Table 1. Thirty-one studies have analyzed adults (2, 4, 6, 10, 11, 15, 16, 23, 24, 27, 30, 36–40, 42, 44, 46–49, 51–54, 56, 61, 62, 65, 73) (26.3 ± 4.5 years), and 10 studies (3, 17, 20, 26, 28, 36, 48, 66, 67, 70) analyzed elderly (63.9 ± 3.8 years). The total number of subjects was of 572, with a mean of 14 ± 7 subjects per study (minimum of 6 and a maximum of 60 subjects per study).

From the 40 studies included, 21 (3, 4, 10, 11, 15, 17, 23, 24, 31, 36, 38, 40, 42, 51–54, 56, 62, 70, 73) performed the walking at the pool floor, while 20 (2, 16, 20, 23, 26–28, 30, 37, 39, 44, 46–49, 61, 65–67, 73) performed the walking at motorized treadmill, and one (6) at non-motorized treadmill. Eighteen studies controlled the walking speed (3, 4, 11, 15, 17, 24, 26, 31, 36, 38, 40, 47, 51–53, 56, 62, 70) by self-selected determination of speed, 17 studies (2, 16, 20, 23, 27, 30, 37, 39, 44, 46, 48, 49, 61, 65–67, 73) used treadmill control, six studies (6, 10, 16, 23, 47, 54) used metronome frequency determination, one study (28) used HR levels to determine the walking intensity, and two studies (42, 73) controlled the speed of walking by synchronizing the volunteer location against markers in the space.

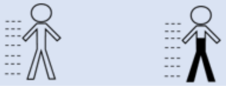
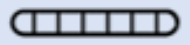
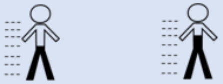
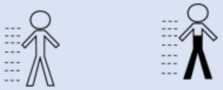
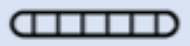
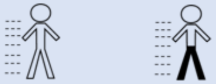
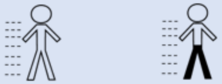
The upper limb orientation during the walking in water was not described in 28 studies (2, 6, 15–17, 20, 23, 24, 26–28, 31, 38–40, 42, 46–49, 51–54, 62, 65, 70, 73), while five studies (30, 44, 61, 66, 67) allowed upper limb swing, five studies (3, 4, 36, 37, 56) oriented to maintain the upper limbs outside of water, and two studies (10, 11) oriented to cross arms at the chest.

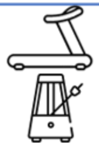
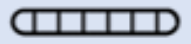
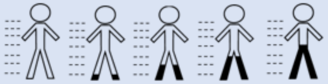
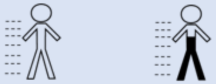
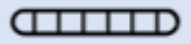
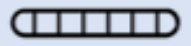
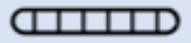
About water temperature, nine studies (3, 4, 10, 17, 31, 36, 42, 54, 62) did not report water temperature, two reported the range 30 to 31º C (23, 44) and one study reported 25.0 to 27.2 ºC (73). For the other 28 studies (2, 6, 11, 15, 16, 20, 24, 26–28, 30, 37–40, 46–49, 51–53, 56, 61, 65–67, 70) the mean temperature was 30.5 ± 2.2º C, with a minimum of 16.7º C (40) and a maximum of 35.8º C (30).

About the depths studied, 38 studies (2–4, 10, 11, 15–17, 20, 23, 24, 26–28, 30, 31, 36, 38–40, 42, 44, 46–49, 51–54, 56, 61, 62, 65–67, 70, 73) used land as a comparator of SWW. The water depth was determined by anatomical landmarks: ankle (27); knee (27); thigh (27, 61); iliac crest (6, 20, 28); waist (23, 37, 39, 73); umbilicus

(16, 27, 61); xiphoid (2–4, 6, 10, 11, 15, 17, 26, 30, 44, 46–49, 56, 62, 65–67); 0.1 m below xiphoid (2); 0.1 m above xiphoid (2); 0.05 to 0.10 m above xiphoid (15); axillar (51–53, 70); neck (37). In terms of absolute depth, the values were: 0.4 m depth (54); 0.5 m depth (40); 0.7 m depth (54); 0.96 m depth (42); 1.0 m depth (54); 1.1 m depth (31, 38); 1.2 m depth (24, 36, 42, 54); 1.3 m depth (31).

Table 1 - Characteristics of the included studies

						Variables							
Study	**N (male)**	**Age**	**Depths**	**Floor or treadmill**	**Speed control**	**ST**	**AA**	**EMG**	**VO2**	**HR**	**GRF**	**JM**	**RPE**
Alkurdi et al. 2010	18 (0)	45 ± 1.3	 **+ 0.1 m** **- 0.1 m**						X	X			X
Barela & Duarte, 2008	10 (6)	70 ± 4.5				X	X	X			X		
Barela et al., 2006	10 (4)	29 ± 6				X	X	X			X		
Benelli et al., 2014	15 (0)	43 ± 3.7		 **(Non-motorized)**		X			X	X			X
Cadenas-Sanchez et al., 2015	8 (4)	22 ± 1.1				X							
Carneiro et al., 2012	22 (11)	24.6 ± 2.6				X	X						
Chevustchi et al., 2009	31 (16)	22.8 ± 1.8	 **+ 0.05 to 0.1 m**			X							
Conti et al., 2015	8 (NI)	26.5 ± 2.8			**Land:**  **Water:** 				X	X			
Degani & Danna-dos-Santos, 2007	8 (NI)	62.5					X						
Dolbow et al., 2008	20 (13)	58.0 ± 2.1							X	X			X

Evans et al., 1978	6 (6)	21 to 42		**Land:** **Water:** 	**Land:** **Water:** 				**X**	**X**		
Fantozzi et al., 2015	11 (6)	27.0 ± 3.4	 **1.2 m**			**X**	**X**					
Fujishima & Shimizu, 2003	9 (9)	67.9 ± 1.7							**X**	**X**		
Gleim & Nicholas, 1989	11 (6)	27.5 ± 1.8							**X**	**X**		
Gobbo et al., 2014	18 (18)	64.2 ± 2.9							**X**	**X**		**X**
Hall et al., 1998	8 (0)	30.2				**X**			**X**	**X**		**X**
Harrison et al., 1992	9 (3)	NI	 **1.1 m** **1.3 m**								**X**	
Jabbar et al., 2017	51 (51)	A:24.6 ± 4.9 B: 58.5 ± 5.1	 **1.2 m**			**X**	**X**					
Jung et al., 2018	15 (9)	37.1 ± 10.9				**X**	**X**					
Kaneda et al., 2007	9 (9)	24.9 ± 2.2	 **1.1 m**					**X**				
Kato et al., 2001	6 (6)	19.8 ± 1.3				**X**	**X**		**X**			
Kotani et al., 2009	8 (8)	22.8 ± 1.0	 **0.5 m**			**X**		**X**				

Kuliukas et al., 2009	30 (14)	39.1 ± 15.4	♙ **0.96 m**	**1.2 m**	▭	⏱				X				
Lim & Rhi, 2014	9 (9)	23.2 ± 1.2	♙	♟	⊿	⊿				X	X			X
Masumoto et al., 2004	6 (6)	23.3 ± 1.4	♙	♟	⊿	⊿			X	X				
Masumoto et al., 2008	9 (0)	61.8 ± 3.8	♙	♟	⊿	⊿	X		X	X	X			X
Masumoto et al., 2012	7 (7)	21.6 ± 1.1	♙	♟	⊿	⊿	X			X	X			X
Masumoto et al., 2013	11 (11)	23.8 ± 4.2	♙	♟	⊿	🚶 ⏲	X			X	X			X
Miyoshi et al., 2003	8 (8)	23.0 ± 2.3	♙	♟	▭	🚶		X					X	
Miyoshi et al., 2004	15 (15)	22.8 ± 4.5	♙	♟	▭	🚶	X	X	X			X	X	
Miyoshi et al., 2005	16 (12)	22.3 ± 2.7	♙	♟	▭	🚶	X		X				X	
Nakazawa et al., 1994	6 (4)	25.5 ± 2.3	**0.4 m** **0.7 m**	**1.0 m** **1.2 m**	▭	⏲	X		X			X		
Orselli & Duarte, 2011	10 (4)	24 ± 3	♙	♟	▭	🚶	X	X				X	X	
Pohl & McNaughton, 2003	6 (NI)	23.2 ± 2.9	♟	♟	⊿	⊿	X			X	X			
Ribas et al., 2007	19 (19)	24.1 ± 3.3	♙	♟	▭	🚶		X						

923

Shimizu et al., 1998	8 (8)	19 ± 1	🧍	🧍	Treadmill	Treadmill				X	X	
Shono et al., 2001	6 (0)	62.2 ± 4.2	🧍	🧍	Treadmill	Treadmill	X			X	X	
Shono et al., 2007	8 (0)	61.4 ± 3.9	🧍	🧍	Treadmill	Treadmill	X	X	X	X	X	
Takeshima et al., 1997	15 (8)	79.9 ± 4.2	🧍	🧍	Floor	🚶	X			X	X	X
Whitley & Schoene, 1987	12 (0)	24.5 ± 5.4	🧍	🧍	**Land:** Treadmill **Water:** Floor	**Land:** Treadmill **Water:** ⏱					X	

Depths		**Walking surface**		**Speed control**			
Anatomical reference	🧍	**Floor**	Floor	**Heart Rate**	♡	**Self-Selected**	🚶
Metric reference	0.7 m	**Treadmill**	Treadmill	**Metronome**	Metronome	**Treadmill**	Treadmill
						Timed Lap	⏱

AA: articular angular; EMG: muscular activity; GRF: ground reaction forces; HR: heart rate; JM: joint moments; NI: not informed; RPE: rating of perceived exertion; ST: spatiotemporal; VO2: energy expenditure. The depth of immersion in anatomical reference are (from shallower to deeper): dry land, ankle, knee, thigh, waist, xiphoid, axillar, neck.

Methodological quality

The methodological quality results are in Table 2. One study (31) was classified with low quality, seven (23, 38, 40, 42, 49, 54, 66) with moderate quality, and all the others were classified as high quality.

Table 2 - Methodological quality analysis.

Study	**Q1**	**Q2**	**Q3**	**Q6**	**Q7**	**Q10**	**Q18**	**Q20**	**Score (Absolute/ Percentual)**	**Quality Rate**
Alkurdi et al. 2010	2	2	2	2	2	1	2	2	(15 / 94%)	High
Barela & Duarte, 2008	2	2	2	2	2	2	2	2	(16 / 100%)	High
Barela et al., 2006	2	2	2	2	2	0	2	2	(14 / 88%)	High
Benelli et al., 2014	2	2	1	1	2	0	2	2	(12 / 75%)	High
Cadenas-Sanchez et al., 2015	2	2	2	2	2	2	2	2	(16 / 100%)	High
Carneiro et al., 2012	2	2	2	2	2	2	2	2	(16 / 100%)	High
Chevustchi et al., 2009	2	2	2	2	2	0	2	2	(14 / 88%)	High
Conti et al., 2015	2	2	1	2	2	0	2	2	(13 / 81%)	High

Degani & Danna-dos-Santos, 2007	2	2	2	2	2	2	2	2	(16 / 100%)	High
Dolbow et al., 2008	2	2	2	2	2	2	2	2	(16 / 100%)	High
Evans et al., 1978	2	2	2	0	0	0	2	2	(10 / 63%)	Moderate
Fantozzi et al., 2015	2	2	1	2	2	0	2	2	(13 / 81%)	High
Fujishima & Shimizu, 2003	2	2	1	1	2	0	2	2	(12 / 75%)	High
Gleim & Nicholas, 1989	2	2	2	2	2	0	2	2	(14 / 88%)	High
Gobbo et al., 2014	2	2	2	2	2	2	2	2	(16 / 100%)	High
Hall et al., 1998	2	2	2	2	2	2	2	2	(16 / 100%)	High
Harrison et al., 1992	2	0	1	0	0	0	0	2	(5 / 31%)	Low
Jabbar et al., 2017	2	2	2	2	2	2	2	2	(16 / 100%)	High
Jung et al., 2018	2	2	2	2	2	2	2	2	(16 / 100%)	High

Kaneda et al., 2007	2	2	1	0	1	0	2	2	(10 / 63%)	Moderate
Kato et al., 2001	2	2	2	2	2	0	2	2	(14 / 88%)	High
Kotani et al., 2009	1	2	2	0	1	0	1	2	(9 / 56%)	Moderate
Kuliukas et al., 2009	2	0	0	0	1	2	2	2	(9 / 56%)	Moderate
Lim & Rhi, 2014	2	2	2	2	2	0	2	2	(14 / 88%)	High
Masumoto et al., 2004	2	2	2	0	0	0	2	2	(10 / 63%)	Moderate
Masumoto et al., 2008	2	2	2	2	2	0	2	2	(14 / 88%)	High
Masumoto et al., 2012	2	2	2	2	2	0	2	2	(14 / 88%)	High
Masumoto et al., 2013	2	2	2	2	2	1	2	2	(15 / 94%)	High
Miyoshi et al., 2003	2	2	2	0	1	0	2	2	(11 / 69%)	High
Miyoshi et al., 2004	2	2	2	0	2	0	2	2	(12 / 75%)	High
Miyoshi et al., 2005	2	2	2	1	2	0	2	2	(13 / 82%)	High
Nakazawa et al., 1994	2	2	0	0	0	0	2	2	(8 / 50%)	Moderate

Orselli & Duarte, 2011	2	2	2	2	2	2	2	2	(16 / 100%)	High
Pohl & McNaughton, 2003	2	2	2	2	2	2	2	2	(16 / 100%)	High
Ribas et al., 2007	2	2	2	2	2	0	2	2	(14 / 88%)	High
Shimizu et al., 1998	2	2	2	1	2	0	2	2	(13 / 81%)	High
Shono et al., 2001	1	1	1	1	2	0	2	2	(10 / 63%)	Moderate
Shono et al., 2007	2	2	1	2	2	2	2	2	(15 / 94%)	High
Takeshima et al., 1997	2	2	2	2	2	0	2	2	(14 / 88%)	High
Whitley & Schoene, 1987	2	2	0	2	2	0	2	2	(12 / 75%)	High

Q.1: “Is the hypothesis/aim/objective of the study clearly described?”. **Q.2:** “Are the main outcomes to be measured clearly described in the Introduction or Methods section?”. **Q.3:** “Are the characteristics of the patients included in the study clearly described?”. **Q.6:** “Are the main findings of the study clearly described?”. **Q.7:** “Does the study provide estimates of the random variability in the data for the main outcomes?”. **Q.10:** “Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?”. **Q.18:** “Were the statistical tests used to assess the main outcomes appropriate?”. **Q.20:** “Were the main outcome measures used accurate (valid and reliable)?”.

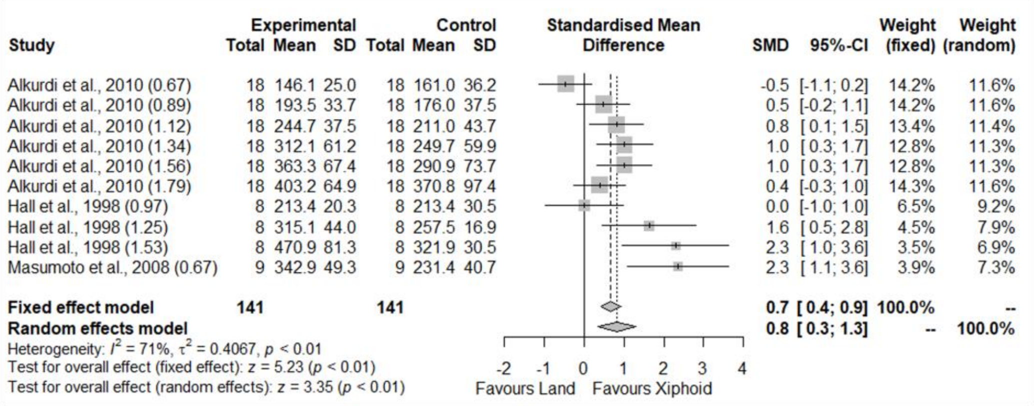
Energy expenditure

Twenty studies (2, 6, 16, 20, 23, 26–28, 30, 39, 42, 44, 46–48, 61, 65–67, 70) have analyzed energy expenditure during walking. Except for Benelli et al. (6) that have compared exclusively two water depths conditions, all studies have compared energy expenditure between shallow water and dry land walking. All 20 studies have analyzed the energy expenditure normalized in the time domain, i.e., metabolic power (PMet), while only one (42) also have analyzed energy expenditure normalized in the space domain, i.e., cost of transport (C).

From the twenty studies that evaluated energy expenditure, seven were included in meta-analysis (2, 20, 27, 30, 39, 48, 61). Thirteen were not included in meta-analysis for different reasons: compared different walking speeds between depths (26, 28, 44, 46, 70), controlled the stride frequency not the walking speed (47), evaluated a submaximal incremental test (16), do not have provided enough data information (23, 64–66), and evaluated different depths than the other studies (6, 42).

The PMet (J/kg/min) was higher in SWW at xiphoid depth than in DLW at even walking speed (SDM = 0.80; 95% CI: 0.32 to 1.28; $p < 0.01$; I^2: 74%; 304.1 ± 105.1 vs. 252.0 ± 60.9 J/kg/min) (Figure 8.A).

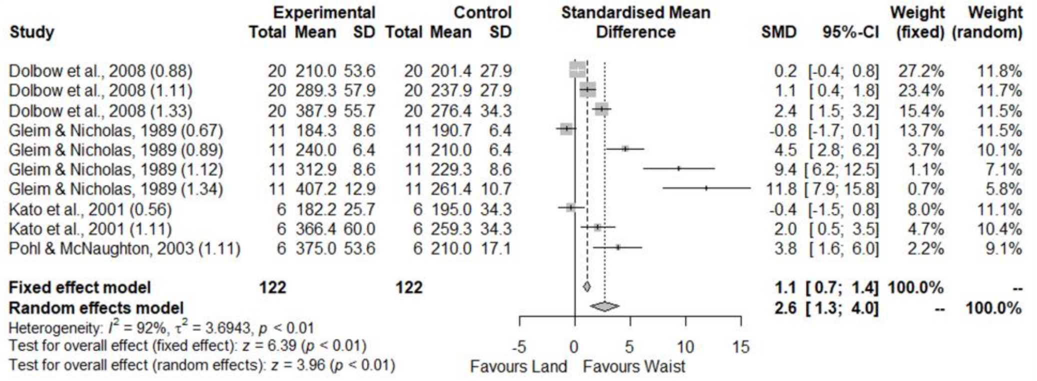
A. Metabolic Power: xiphoid depth vs. dry land



	Experimental			Control					Weight	Weight
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	(fixed)	(random)
Alkurdi et al., 2010 (0.67)	18	146.1	25.0	18	161.0	36.2	-0.5	[-1.1; 0.2]	14.2%	11.6%
Alkurdi et al., 2010 (0.89)	18	193.5	33.7	18	176.0	37.5	0.5	[-0.2; 1.1]	14.2%	11.6%
Alkurdi et al., 2010 (1.12)	18	244.7	37.5	18	211.0	43.7	0.8	[0.1; 1.5]	13.4%	11.4%
Alkurdi et al., 2010 (1.34)	18	312.1	61.2	18	249.7	59.9	1.0	[0.3; 1.7]	12.8%	11.3%
Alkurdi et al., 2010 (1.56)	18	363.3	67.4	18	290.9	73.7	1.0	[0.3; 1.7]	12.8%	11.3%
Alkurdi et al., 2010 (1.79)	18	403.2	64.9	18	370.8	97.4	0.4	[-0.3; 1.0]	14.3%	11.6%
Hall et al., 1998 (0.97)	8	213.4	20.3	8	213.4	30.5	0.0	[-1.0; 1.0]	6.5%	9.2%
Hall et al., 1998 (1.25)	8	315.1	44.0	8	257.5	16.9	1.6	[0.5; 2.8]	4.5%	7.9%
Hall et al., 1998 (1.53)	8	470.9	81.3	8	321.9	30.5	2.3	[1.0; 3.6]	3.5%	6.9%
Masumoto et al., 2008 (0.67)	9	342.9	49.3	9	231.4	40.7	2.3	[1.1; 3.6]	3.9%	7.3%
Fixed effect model	**141**			**141**			**0.7**	**[0.4; 0.9]**	**100.0%**	--
Random effects model							**0.8**	**[0.3; 1.3]**	--	**100.0%**

Heterogeneity: $I^2 = 71\%$, $\tau^2 = 0.4067$, $p < 0.01$
Test for overall effect (fixed effect): $z = 5.23$ ($p < 0.01$)
Test for overall effect (random effects): $z = 3.35$ ($p < 0.01$)

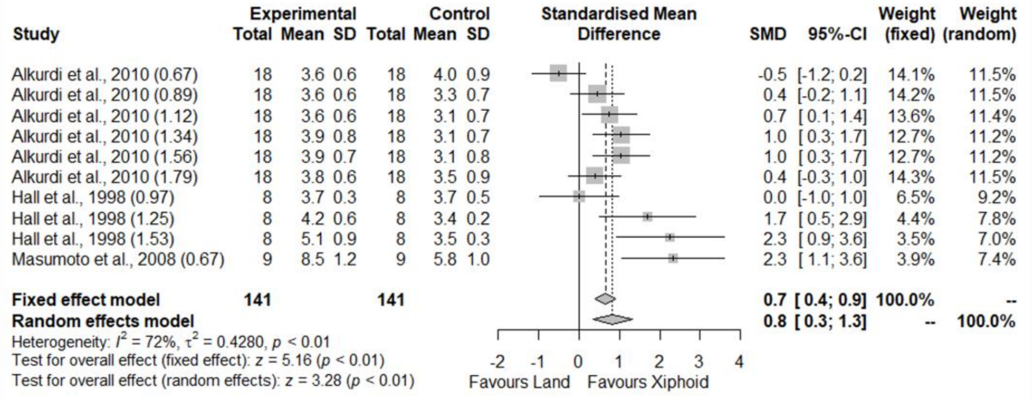
B. Metabolic Power: waist depth vs. dry land



	Experimental			Control					Weight	Weight
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	(fixed)	(random)
Dolbow et al., 2008 (0.88)	20	210.0	53.6	20	201.4	27.9	0.2	[-0.4; 0.8]	27.2%	11.8%
Dolbow et al., 2008 (1.11)	20	289.3	57.9	20	237.9	27.9	1.1	[0.4; 1.8]	23.4%	11.7%
Dolbow et al., 2008 (1.33)	20	387.9	55.7	20	276.4	34.3	2.4	[1.5; 3.2]	15.4%	11.5%
Gleim & Nicholas, 1989 (0.67)	11	184.3	8.6	11	190.7	6.4	-0.8	[-1.7; 0.1]	13.7%	11.5%
Gleim & Nicholas, 1989 (0.89)	11	240.0	6.4	11	210.0	6.4	4.5	[2.8; 6.2]	3.7%	10.1%
Gleim & Nicholas, 1989 (1.12)	11	312.9	8.6	11	229.3	8.6	9.4	[6.2; 12.5]	1.1%	7.1%
Gleim & Nicholas, 1989 (1.34)	11	407.2	12.9	11	261.4	10.7	11.8	[7.9; 15.8]	0.7%	5.8%
Kato et al., 2001 (0.56)	6	182.2	25.7	6	195.0	34.3	-0.4	[-1.5; 0.8]	8.0%	11.1%
Kato et al., 2001 (1.11)	6	366.4	60.0	6	259.3	34.3	2.0	[0.5; 3.5]	4.7%	10.4%
Pohl & McNaughton, 2003 (1.11)	6	375.0	53.6	6	210.0	17.1	3.8	[1.6; 6.0]	2.2%	9.1%
Fixed effect model	**122**			**122**			**1.1**	**[0.7; 1.4]**	**100.0%**	--
Random effects model							**2.6**	**[1.3; 4.0]**	--	**100.0%**

Heterogeneity: $I^2 = 92\%$, $\tau^2 = 3.6943$, $p < 0.01$
Test for overall effect (fixed effect): $z = 6.39$ ($p < 0.01$)
Test for overall effect (random effects): $z = 3.96$ ($p < 0.01$)

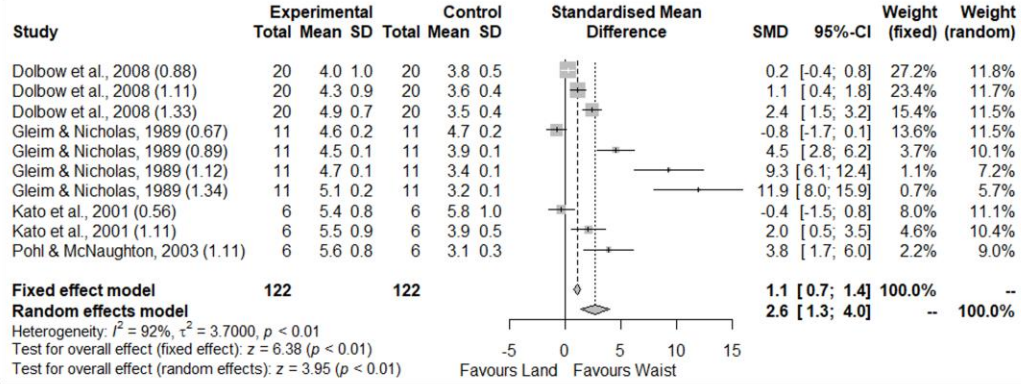
C. Cost of transport: xiphoid depth vs. dry land



	Experimental			Control					Weight	Weight
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	(fixed)	(random)
Alkurdi et al., 2010 (0.67)	18	3.6	0.6	18	4.0	0.9	-0.5	[-1.2; 0.2]	14.1%	11.5%
Alkurdi et al., 2010 (0.89)	18	3.6	0.6	18	3.3	0.7	0.4	[-0.2; 1.1]	14.2%	11.5%
Alkurdi et al., 2010 (1.12)	18	3.6	0.6	18	3.1	0.7	0.7	[0.1; 1.4]	13.6%	11.4%
Alkurdi et al., 2010 (1.34)	18	3.9	0.8	18	3.1	0.7	1.0	[0.3; 1.7]	12.7%	11.2%
Alkurdi et al., 2010 (1.56)	18	3.9	0.7	18	3.1	0.8	1.0	[0.3; 1.7]	12.7%	11.2%
Alkurdi et al., 2010 (1.79)	18	3.8	0.6	18	3.5	0.9	0.4	[-0.3; 1.0]	14.3%	11.5%
Hall et al., 1998 (0.97)	8	3.7	0.3	8	3.7	0.5	0.0	[-1.0; 1.0]	6.5%	9.2%
Hall et al., 1998 (1.25)	8	4.2	0.6	8	3.4	0.2	1.7	[0.5; 2.9]	4.4%	7.8%
Hall et al., 1998 (1.53)	8	5.1	0.9	8	3.5	0.3	2.3	[0.9; 3.6]	3.5%	7.0%
Masumoto et al., 2008 (0.67)	9	8.5	1.2	9	5.8	1.0	2.3	[1.1; 3.6]	3.9%	7.4%
Fixed effect model	**141**			**141**			**0.7**	**[0.4; 0.9]**	**100.0%**	--
Random effects model							**0.8**	**[0.3; 1.3]**	--	**100.0%**

Heterogeneity: $I^2 = 72\%$, $\tau^2 = 0.4280$, $p < 0.01$
Test for overall effect (fixed effect): $z = 5.16$ ($p < 0.01$)
Test for overall effect (random effects): $z = 3.28$ ($p < 0.01$)

D. Cost of transport: waist depth vs. dry land



	Experimental			Control					Weight	Weight
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	(fixed)	(random)
Dolbow et al., 2008 (0.88)	20	4.0	1.0	20	3.8	0.5	0.2	[-0.4; 0.8]	27.2%	11.8%
Dolbow et al., 2008 (1.11)	20	4.3	0.9	20	3.6	0.4	1.1	[0.4; 1.8]	23.4%	11.7%
Dolbow et al., 2008 (1.33)	20	4.9	0.7	20	3.5	0.4	2.4	[1.5; 3.2]	15.4%	11.5%
Gleim & Nicholas, 1989 (0.67)	11	4.6	0.2	11	4.7	0.2	-0.8	[-1.7; 0.1]	13.6%	11.5%
Gleim & Nicholas, 1989 (0.89)	11	4.5	0.1	11	3.9	0.1	4.5	[2.8; 6.2]	3.7%	10.1%
Gleim & Nicholas, 1989 (1.12)	11	4.7	0.1	11	3.4	0.1	9.3	[6.1; 12.4]	1.1%	7.2%
Gleim & Nicholas, 1989 (1.34)	11	5.1	0.2	11	3.2	0.1	11.9	[8.0; 15.9]	0.7%	5.7%
Kato et al., 2001 (0.56)	6	5.4	0.8	6	5.8	1.0	-0.4	[-1.5; 0.8]	8.0%	11.1%
Kato et al., 2001 (1.11)	6	5.5	0.9	6	3.9	0.5	2.0	[0.5; 3.5]	4.6%	10.4%
Pohl & McNaughton, 2003 (1.11)	6	5.6	0.8	6	3.1	0.3	3.8	[1.7; 6.0]	2.2%	9.0%
Fixed effect model	**122**			**122**			**1.1**	**[0.7; 1.4]**	**100.0%**	--
Random effects model							**2.6**	**[1.3; 4.0]**	--	**100.0%**

Heterogeneity: $I^2 = 92\%$, $\tau^2 = 3.7000$, $p < 0.01$
Test for overall effect (fixed effect): $z = 6.38$ ($p < 0.01$)
Test for overall effect (random effects): $z = 3.95$ ($p < 0.01$)

Figure 8 – Panel of metabolic power and cost of transport meta-analysis. **A.** Meta-analysis of metabolic power (J/kg/min) at even walking speed (xiphoid depth vs. dry land). Standard mean differences between walking in the same speed (1.16 ± 0.37 m/s). **B.** Meta-analysis of metabolic power (J/kg/min) at even walking speed (waist depth vs. dry land). Standard mean differences between walking in the same speed (1.19 ± 0.42 m/s). **C.** Meta-analysis of cost of transport (J/kg/m) at even walking speed (xiphoid depth vs. dry land). Standard mean differences between walking in the same speed (1.20 ± 0.35 m/s). **D.** Meta-analysis of cost of transport (J/kg/m) at even walking speed (waist depth vs. dry land). Standard mean differences between walking in the same speed (1.19 ± 0.42 m/s).

The PMet (J/kg/min) was higher in SWW at waist depth than in DLW at even walking speed (SMD = 3.76; 95% CI: 2.38 to 5.14; $p < 0.01$; I^2: 94%; 295.5 ± 87.1 vs. 227.1 ± 30.5 J/kg/min) (Figure 8.B).

The C (J/kg/m) was higher in SWW at xiphoid depth than in DLW at even walking speed (SDM = 0.79; 95% CI: 0.31 to 1.27; $p < 0.01$; I^2: 75; 4.32 ± 1.38 vs. 3.62 ± 0.69 J/kg/m) (Figure 8.C).

The C (J/kg/m) was higher in SWW at waist depth than in DLW at even walking speed (SMD = 3.75; 95% CI: 2.37 to 5.13; $p < 0.01$; I^2: 94%; 4.85 ± 0.54 vs. 3.90 ± 0.81 J/kg/m) (Figure 8.D).

Spatiotemporal parameters

From the 13 studies that reported speed as dependent variable (3, 4, 6, 10, 11, 15, 24, 36, 47, 51, 53, 56, 70), 11 analyzed comfortable speed of walking (3, 4, 11, 15, 24, 36, 47, 51, 53, 56, 70) and three studies analyzed fast speed condition (15, 53, 70). Taking together the studies that have compared different water depths with DLW, both comfortable (0.46 ± 0.06 vs. 1.25 ± 0.13 m/s) and fast (0.63 ± 0.23 vs. 1.74 ± 0.40 m/s) walking speeds were lower in SWW.

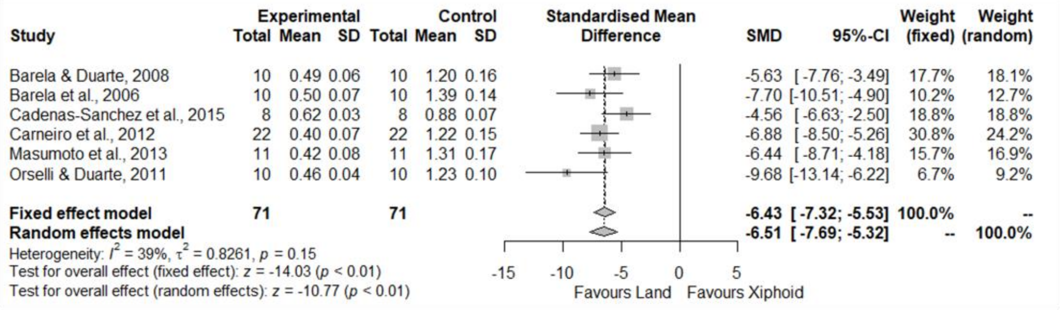
From the 13 studies that analyzed speed as dependent variable, nine were included in meta-analysis (3, 4, 10, 11, 47, 51, 53, 56, 70). Four studies were not included in meta-analysis for different reasons: controlled the intensity by stride frequency (6), evaluated different depths than the other studies (15, 24, 36)

According to the meta-analysis, the SSWS (m/s) was lower in SWW than DLW both at xiphoid depth (SMD = -6.51; 95% CI: -7.69 to -5.32; $p < 0.01$; I^2: 39%; 0.48 ± 0.08 vs. 1.21 ± 0.17 m/s) (Figure 9.A), and at axillar depth (SMD = -6.38; 95% CI: -8.66 to -4.10; $p < 0.01$; I^2: 78%; 0.50 ± 0.09 vs. 1.11 ± 0.13 m/s) (Figure 9.B).

The fast speed (m/s) was lower in SWW at axillar depth than DLW (SMD = -6.25; 95% CI: -12.59 to 0.09; $p = 0.05$; I^2: 95%; 0.69 ± 0.37 vs. 1.40 ± 0.03 m/s) (Figure 9.C).

The duty factor (%) was lower in SWW at xiphoid depth than DLW at self-selected speed (SMD: -1.27; 95%CI: -2.42 to -0.11; $p = 0.03$; I^2: 79%; 60.4 ± 2.6 vs. 63.7 ± 1.9%) (Figure 9.D).

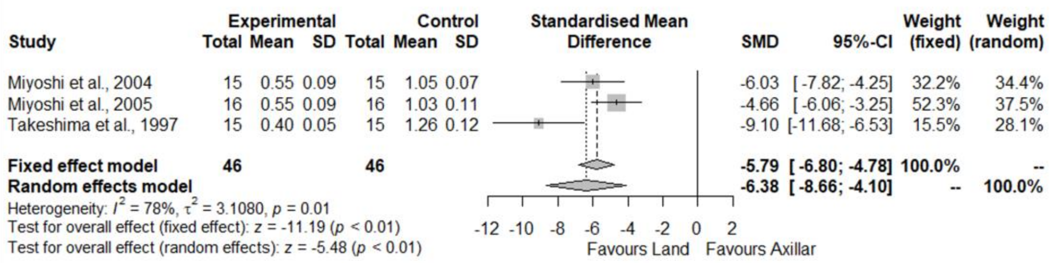
A. Self-selected walking speed: xiphoid depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight	Weight
	Total	Mean	SD	Total	Mean	SD			(fixed)	(random)
Barela & Duarte, 2008	10	0.49	0.06	10	1.20	0.16	-5.63	[-7.76; -3.49]	17.7%	18.1%
Barela et al., 2006	10	0.50	0.07	10	1.39	0.14	-7.70	[-10.51; -4.90]	10.2%	12.7%
Cadenas-Sanchez et al., 2015	8	0.62	0.03	8	0.88	0.07	-4.56	[-6.63; -2.50]	18.8%	18.8%
Carneiro et al., 2012	22	0.40	0.07	22	1.22	0.15	-6.88	[-8.50; -5.26]	30.8%	24.2%
Masumoto et al., 2013	11	0.42	0.08	11	1.31	0.17	-6.44	[-8.71; -4.18]	15.7%	16.9%
Orselli & Duarte, 2011	10	0.46	0.04	10	1.23	0.10	-9.68	[-13.14; -6.22]	6.7%	9.2%
Fixed effect model	**71**			**71**			**-6.43**	**[-7.32; -5.53]**	**100.0%**	--
Random effects model							**-6.51**	**[-7.69; -5.32]**	--	**100.0%**

Heterogeneity: $I^2 = 39\%$, $\tau^2 = 0.8261$, $p = 0.15$
Test for overall effect (fixed effect): $z = -14.03$ ($p < 0.01$)
Test for overall effect (random effects): $z = -10.77$ ($p < 0.01$)

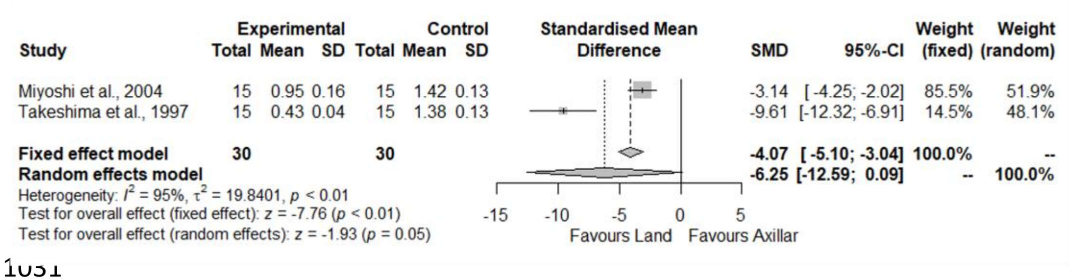
B. Self-selected walking speed: axillar depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight	Weight
	Total	Mean	SD	Total	Mean	SD			(fixed)	(random)
Miyoshi et al., 2004	15	0.55	0.09	15	1.05	0.07	-6.03	[-7.82; -4.25]	32.2%	34.4%
Miyoshi et al., 2005	16	0.55	0.09	16	1.03	0.11	-4.66	[-6.06; -3.25]	52.3%	37.5%
Takeshima et al., 1997	15	0.40	0.05	15	1.26	0.12	-9.10	[-11.68; -6.53]	15.5%	28.1%
Fixed effect model	**46**			**46**			**-5.79**	**[-6.80; -4.78]**	**100.0%**	--
Random effects model							**-6.38**	**[-8.66; -4.10]**	--	**100.0%**

Heterogeneity: $I^2 = 78\%$, $\tau^2 = 3.1080$, $p = 0.01$
Test for overall effect (fixed effect): $z = -11.19$ ($p < 0.01$)
Test for overall effect (random effects): $z = -5.48$ ($p < 0.01$)

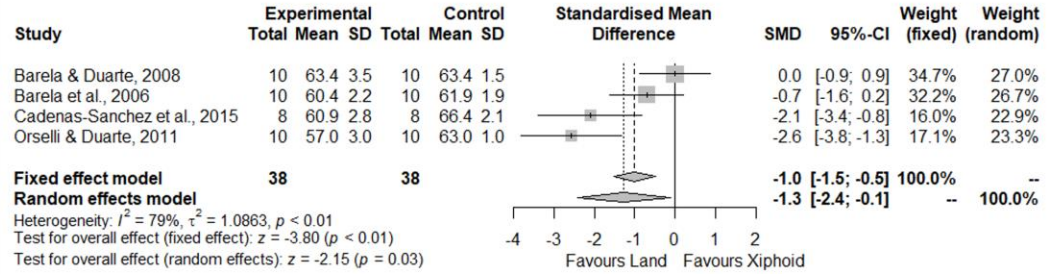
C. Fast walking speed: axillar depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight	Weight
	Total	Mean	SD	Total	Mean	SD			(fixed)	(random)
Miyoshi et al., 2004	15	0.95	0.16	15	1.42	0.13	-3.14	[-4.25; -2.02]	85.5%	51.9%
Takeshima et al., 1997	15	0.43	0.04	15	1.38	0.13	-9.61	[-12.32; -6.91]	14.5%	48.1%
Fixed effect model	**30**			**30**			**-4.07**	**[-5.10; -3.04]**	**100.0%**	--
Random effects model							**-6.25**	**[-12.59; 0.09]**	--	**100.0%**

Heterogeneity: $I^2 = 95\%$, $\tau^2 = 19.8401$, $p < 0.01$
Test for overall effect (fixed effect): $z = -7.76$ ($p < 0.01$)
Test for overall effect (random effects): $z = -1.93$ ($p = 0.05$)

D. Duty factor: xiphoid depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight	Weight
	Total	Mean	SD	Total	Mean	SD			(fixed)	(random)
Barela & Duarte, 2008	10	63.4	3.5	10	63.4	1.5	0.0	[-0.9; 0.9]	34.7%	27.0%
Barela et al., 2006	10	60.4	2.2	10	61.9	1.9	-0.7	[-1.6; 0.2]	32.2%	26.7%
Cadenas-Sanchez et al., 2015	8	60.9	2.8	8	66.4	2.1	-2.1	[-3.4; -0.8]	16.0%	22.9%
Orselli & Duarte, 2011	10	57.0	3.0	10	63.0	1.0	-2.6	[-3.8; -1.3]	17.1%	23.3%
Fixed effect model	**38**			**38**			**-1.0**	**[-1.5; -0.5]**	**100.0%**	--
Random effects model							**-1.3**	**[-2.4; -0.1]**	--	**100.0%**

Heterogeneity: $I^2 = 79\%$, $\tau^2 = 1.0863$, $p < 0.01$
Test for overall effect (fixed effect): $z = -3.80$ ($p < 0.01$)
Test for overall effect (random effects): $z = -2.15$ ($p = 0.03$)

Figure 9 – Panel of walking speed and duty factor meta-analysis. **A.** Meta-analysis of comfortable self-selected walking speed (m/s) (xiphoid depth vs. dry land). Standard mean differences between conditions. **B.** Meta-analysis of comfortable self-selected speed of walking (m/s) (axillar depth vs. dry land). Standard mean differences between conditions. **C.** Meta-analysis of fast self-selected speed of walking (m/s) (axillar depth vs. dry land). Standard mean differences between conditions. **D.** Meta-analysis of duty factor (%) at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions.

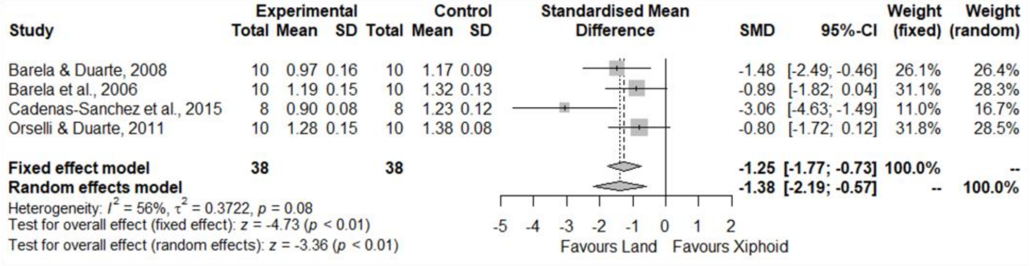
The stride length (m) was lower in SWW at xiphoid depth than DLW at self-selected speed (SMD = -1.38; 95% CI: -2.19 to -0.57; p < 0.01; I^2: 56%; 1.09 ± 0.18 vs. 1.28 ± 0.09 m) (Figure 10.A).

The stride duration (s) was higher in SWW at xiphoid depth than DLW in self-selected speed (SMD: 6.40; 95%CI: 4.29 to 8.50; p < 0.01; I^2: 64%; 2.4 ± 0.4 vs. 1.0 ± 0.1 s) (Figure 10.B).

The stride frequency (strides/min) was lower in SWW at xiphoid depth than DLW at even speed (SMD: -4.67; 95%CI: -6.99 to -2.35; p < 0.01; I^2: 80%; 84.7 ± 9.6 vs. 114.7 ± 8.6 strides/min) (Figure 10.C).

The stride frequency was similar in SWW at waist depth than DLW at even walking speed (SMD: -0.56; 95%CI: -1.24 to 0.12; p = 0.10; I^2: 0%; 63.7 ± 25.4 vs. 72.4 ± 26.7 strides/min) (Figure 10.D).

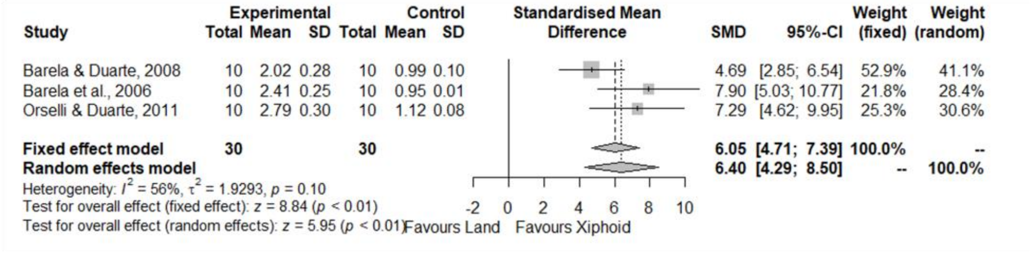
A. Stride length: xiphoid depth vs. dry land



Study	Experimental Total	Experimental Mean	Experimental SD	Control Total	Control Mean	Control SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Barela & Duarte, 2008	10	0.97	0.16	10	1.17	0.09	-1.48	[-2.49; -0.46]	26.1%	26.4%
Barela et al., 2006	10	1.19	0.15	10	1.32	0.13	-0.89	[-1.82; 0.04]	31.1%	28.3%
Cadenas-Sanchez et al., 2015	8	0.90	0.08	8	1.23	0.12	-3.06	[-4.63; -1.49]	11.0%	16.7%
Orselli & Duarte, 2011	10	1.28	0.15	10	1.38	0.08	-0.80	[-1.72; 0.12]	31.8%	28.5%
Fixed effect model	**38**			**38**			**-1.25**	**[-1.77; -0.73]**	**100.0%**	--
Random effects model							**-1.38**	**[-2.19; -0.57]**	--	**100.0%**

Heterogeneity: $I^2 = 56\%$, $\tau^2 = 0.3722$, $p = 0.08$
Test for overall effect (fixed effect): $z = -4.73$ ($p < 0.01$)
Test for overall effect (random effects): $z = -3.36$ ($p < 0.01$)

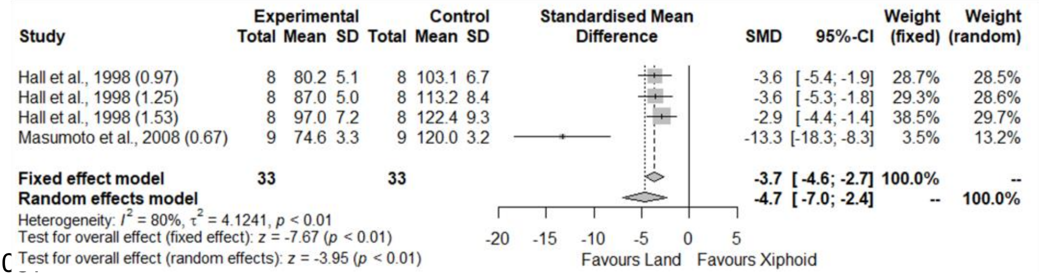
B. Stride duration: xiphoid depth vs. dry land



Study	Experimental Total	Experimental Mean	Experimental SD	Control Total	Control Mean	Control SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Barela & Duarte, 2008	10	2.02	0.28	10	0.99	0.10	4.69	[2.85; 6.54]	52.9%	41.1%
Barela et al., 2006	10	2.41	0.25	10	0.95	0.01	7.90	[5.03; 10.77]	21.8%	28.4%
Orselli & Duarte, 2011	10	2.79	0.30	10	1.12	0.08	7.29	[4.62; 9.95]	25.3%	30.6%
Fixed effect model	**30**			**30**			**6.05**	**[4.71; 7.39]**	**100.0%**	--
Random effects model							**6.40**	**[4.29; 8.50]**	--	**100.0%**

Heterogeneity: $I^2 = 56\%$, $\tau^2 = 1.9293$, $p = 0.10$
Test for overall effect (fixed effect): $z = 8.84$ ($p < 0.01$)
Test for overall effect (random effects): $z = 5.95$ ($p < 0.01$)

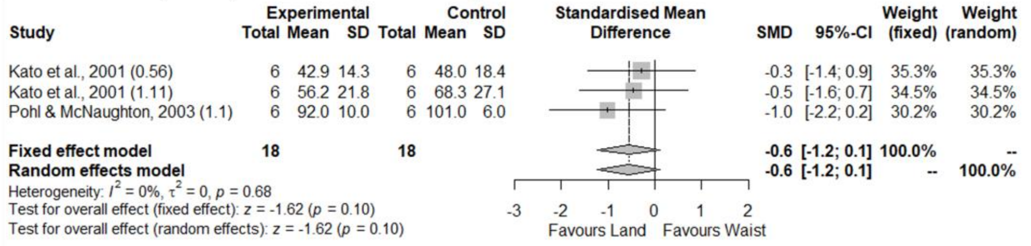
C. Stride frequency: xiphoid depth vs. dry land



Study	Experimental Total	Experimental Mean	Experimental SD	Control Total	Control Mean	Control SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Hall et al., 1998 (0.97)	8	80.2	5.1	8	103.1	6.7	-3.6	[-5.4; -1.9]	28.7%	28.5%
Hall et al., 1998 (1.25)	8	87.0	5.0	8	113.2	8.4	-3.6	[-5.3; -1.8]	29.3%	28.6%
Hall et al., 1998 (1.53)	8	97.0	7.2	8	122.4	9.3	-2.9	[-4.4; -1.4]	38.5%	29.7%
Masumoto et al., 2008 (0.67)	9	74.6	3.3	9	120.0	3.2	-13.3	[-18.3; -8.3]	3.5%	13.2%
Fixed effect model	**33**			**33**			**-3.7**	**[-4.6; -2.7]**	**100.0%**	--
Random effects model							**-4.7**	**[-7.0; -2.4]**	--	**100.0%**

Heterogeneity: $I^2 = 80\%$, $\tau^2 = 4.1241$, $p < 0.01$
Test for overall effect (fixed effect): $z = -7.67$ ($p < 0.01$)
Test for overall effect (random effects): $z = -3.95$ ($p < 0.01$)

D. Stride frequency: waist depth vs. dry land



Study	Experimental Total	Experimental Mean	Experimental SD	Control Total	Control Mean	Control SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Kato et al., 2001 (0.56)	6	42.9	14.3	6	48.0	18.4	-0.3	[-1.4; 0.9]	35.3%	35.3%
Kato et al., 2001 (1.11)	6	56.2	21.8	6	68.3	27.1	-0.5	[-1.6; 0.7]	34.5%	34.5%
Pohl & McNaughton, 2003 (1.1)	6	92.0	10.0	6	101.0	6.0	-1.0	[-2.2; 0.2]	30.2%	30.2%
Fixed effect model	**18**			**18**			**-0.6**	**[-1.2; 0.1]**	**100.0%**	--
Random effects model							**-0.6**	**[-1.2; 0.1]**	--	**100.0%**

Heterogeneity: $I^2 = 0\%$, $\tau^2 = 0$, $p = 0.68$
Test for overall effect (fixed effect): $z = -1.62$ ($p = 0.10$)
Test for overall effect (random effects): $z = -1.62$ ($p = 0.10$)

Figure 10 – Panel of stride length, stride duration and stride frequency meta-analysis. **A.** Meta-analysis of stride length (m) at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions. **B.** Meta-analysis of stride duration (s) at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions. **C.** Meta-analysis of stride frequency (strides/min) at even walking speed (xiphoid depth vs. dry land). Standard mean differences between walking in the same speed (1.11 ± 0.37 m/s). **D.** Meta-analysis of stride frequency (strides/min) at even walking speed (waist depth vs. dry land). Standard mean differences between walking in the same speed (0.92 ± 0.31 m/s).

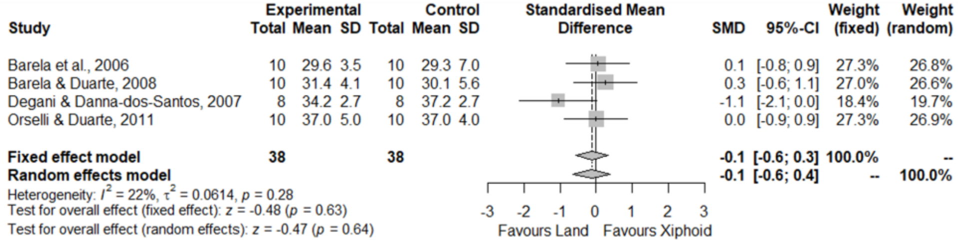
Joint kinematics

The hip ROM was similar in SWW at xiphoid depth and DLW at self-selected speed (SMD: -0.12; 95%CI: -0.64 to 0.39; p = 0.64; I^2: 22%; 33.1 ± 3.2 vs. 33.4 ± 4.3 º) (Figure 11.A).

The knee ROM was lower in SWW at xiphoid depth than DLW at self-selected speed (SMD: -0.62; 95%CI: -1.17 to -0.06; p = 0.03; I^2: 27%; 55.6 ± 7.9 vs. 59.0 ± 6.6 º) (Figure 11.B).

The ankle ROM was similar in SWW at xiphoid depth than DLW at self-selected speed (SMD: -0.84; 95%CI: -2.15 to 0.47; p = 0.31; I^2: 84%; 25.9 ± 7.4 vs. 28.3 ± 3.9 º) (Figure 11.C).

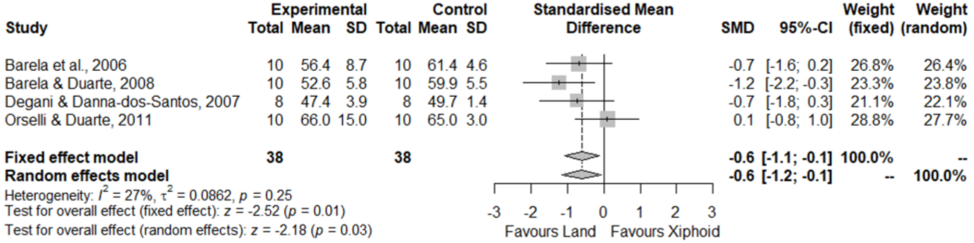
A. Hip total range of motion: xiphoid depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight (fixed)	Weight (random)
	Total	Mean	SD	Total	Mean	SD				
Barela et al., 2006	10	29.6	3.5	10	29.3	7.0	0.1	[-0.8; 0.9]	27.3%	26.8%
Barela & Duarte, 2008	10	31.4	4.1	10	30.1	5.6	0.3	[-0.6; 1.1]	27.0%	26.6%
Degani & Danna-dos-Santos, 2007	8	34.2	2.7	8	37.2	2.7	-1.1	[-2.1; 0.0]	18.4%	19.7%
Orselli & Duarte, 2011	10	37.0	5.0	10	37.0	4.0	0.0	[-0.9; 0.9]	27.3%	26.9%
Fixed effect model	**38**			**38**			**-0.1**	**[-0.6; 0.3]**	**100.0%**	**--**
Random effects model							**-0.1**	**[-0.6; 0.4]**	**--**	**100.0%**

Heterogeneity: $I^2 = 22\%$, $\tau^2 = 0.0614$, $p = 0.28$
Test for overall effect (fixed effect): $z = -0.48$ ($p = 0.63$)
Test for overall effect (random effects): $z = -0.47$ ($p = 0.64$)

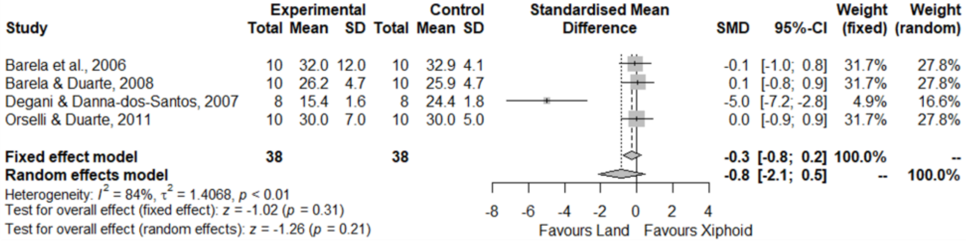
B. Knee total range of motion: xiphoid depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight (fixed)	Weight (random)
	Total	Mean	SD	Total	Mean	SD				
Barela et al., 2006	10	56.4	8.7	10	61.4	4.6	-0.7	[-1.6; 0.2]	26.8%	26.4%
Barela & Duarte, 2008	10	52.6	5.8	10	59.9	5.5	-1.2	[-2.2; -0.3]	23.3%	23.8%
Degani & Danna-dos-Santos, 2007	8	47.4	3.9	8	49.7	1.4	-0.7	[-1.8; 0.3]	21.1%	22.1%
Orselli & Duarte, 2011	10	66.0	15.0	10	65.0	3.0	0.1	[-0.8; 1.0]	28.8%	27.7%
Fixed effect model	**38**			**38**			**-0.6**	**[-1.1; -0.1]**	**100.0%**	**--**
Random effects model							**-0.6**	**[-1.2; -0.1]**	**--**	**100.0%**

Heterogeneity: $I^2 = 27\%$, $\tau^2 = 0.0862$, $p = 0.25$
Test for overall effect (fixed effect): $z = -2.52$ ($p = 0.01$)
Test for overall effect (random effects): $z = -2.18$ ($p = 0.03$)

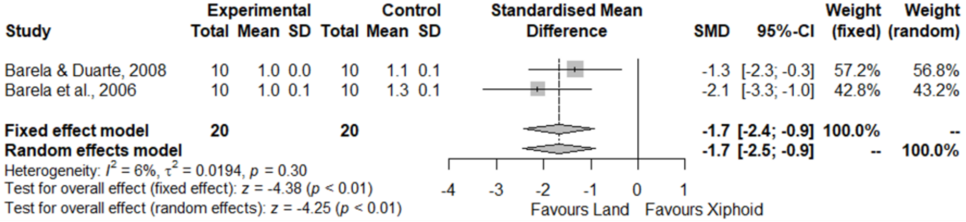
C. Ankle total range of motion: xiphoid depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight (fixed)	Weight (random)
	Total	Mean	SD	Total	Mean	SD				
Barela et al., 2006	10	32.0	12.0	10	32.9	4.1	-0.1	[-1.0; 0.8]	31.7%	27.8%
Barela & Duarte, 2008	10	26.2	4.7	10	25.9	4.7	0.1	[-0.8; 0.9]	31.7%	27.8%
Degani & Danna-dos-Santos, 2007	8	15.4	1.6	8	24.4	1.8	-5.0	[-7.2; -2.8]	4.9%	16.6%
Orselli & Duarte, 2011	10	30.0	7.0	10	30.0	5.0	0.0	[-0.9; 0.9]	31.7%	27.8%
Fixed effect model	**38**			**38**			**-0.3**	**[-0.8; 0.2]**	**100.0%**	**--**
Random effects model							**-0.8**	**[-2.1; 0.5]**	**--**	**100.0%**

Heterogeneity: $I^2 = 84\%$, $\tau^2 = 1.4068$, $p < 0.01$
Test for overall effect (fixed effect): $z = -1.02$ ($p = 0.31$)
Test for overall effect (random effects): $z = -1.26$ ($p = 0.21$)

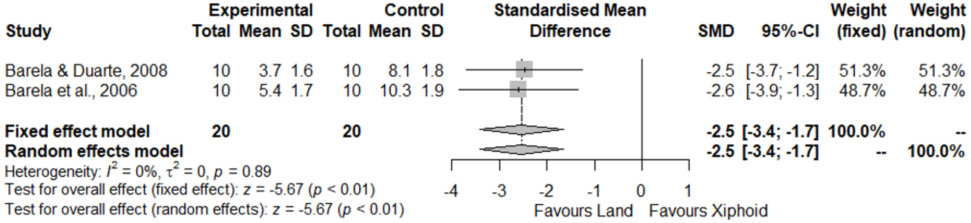
D. Peak vertical ground reaction force: xiphoid depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight (fixed)	Weight (random)
	Total	Mean	SD	Total	Mean	SD				
Barela & Duarte, 2008	10	1.0	0.0	10	1.1	0.1	-1.3	[-2.3; -0.3]	57.2%	56.8%
Barela et al., 2006	10	1.0	0.1	10	1.3	0.1	-2.1	[-3.3; -1.0]	42.8%	43.2%
Fixed effect model	**20**			**20**			**-1.7**	**[-2.4; -0.9]**	**100.0%**	**--**
Random effects model							**-1.7**	**[-2.5; -0.9]**	**--**	**100.0%**

Heterogeneity: $I^2 = 6\%$, $\tau^2 = 0.0194$, $p = 0.30$
Test for overall effect (fixed effect): $z = -4.38$ ($p < 0.01$)
Test for overall effect (random effects): $z = -4.25$ ($p < 0.01$)

E. Rate of force development: xiphoid depth vs. dry land



Study	Experimental			Control			SMD	95%-CI	Weight (fixed)	Weight (random)
	Total	Mean	SD	Total	Mean	SD				
Barela & Duarte, 2008	10	3.7	1.6	10	8.1	1.8	-2.5	[-3.7; -1.2]	51.3%	51.3%
Barela et al., 2006	10	5.4	1.7	10	10.3	1.9	-2.6	[-3.9; -1.3]	48.7%	48.7%
Fixed effect model	**20**			**20**			**-2.5**	**[-3.4; -1.7]**	**100.0%**	**--**
Random effects model							**-2.5**	**[-3.4; -1.7]**	**--**	**100.0%**

Heterogeneity: $I^2 = 0\%$, $\tau^2 = 0$, $p = 0.89$
Test for overall effect (fixed effect): $z = -5.67$ ($p < 0.01$)
Test for overall effect (random effects): $z = -5.67$ ($p < 0.01$)

Figure 5 – Panel of joints total range of motion and ground reaction forces meta-analysis. **A.** Meta-analysis of hip total range of motion at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions. **B.** Meta-analysis of knee total range of motion at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions. **C.** Meta-analysis of ankle total range of motion at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions. **D.** Meta-analysis of peak vertical ground reaction force (N/body weight) during walking at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions. **E.** Meta-analysis of rate of force development (body weight/s) during walking at self-selected speed (xiphoid depth vs. dry land). Standard mean differences between conditions.

Ground reaction forces

The peak of vertical ground reaction force (peak of V-GRF) (N/body weight) was lower in SWW at xiphoid depth than DLW at self-selected speed (SMD: -1.68; 95%CI: -2.45 to -0.90; $p < 0.01$; I^2: 6%; 1.02 ± 0.01 vs. 1.20 ± 0.11 N/body weight) (Figure 11.D). Likewise, the rate of force development (body weight/s) was lower in SWW at xiphoid depth than DLW at self-selected speed (SMD: -2.54; 95%CI: -3.41 to -1.66; $p < 0.01$; I^2: 0%; 4.55 ± 1.20 vs. 9.20 ± 1.56 body weight/s) (Figure 11.E).

Heart rate

The HR was higher in SWW at xiphoid depth than DLW at even walking speed (SMD: 2.10; 95%CI: 1.18 to 3.02; $p < 0.01$; I^2: 91%; 127.9 ± 24.1 vs. 96.3 ± 18.1 bpm) (Figure 12.A).

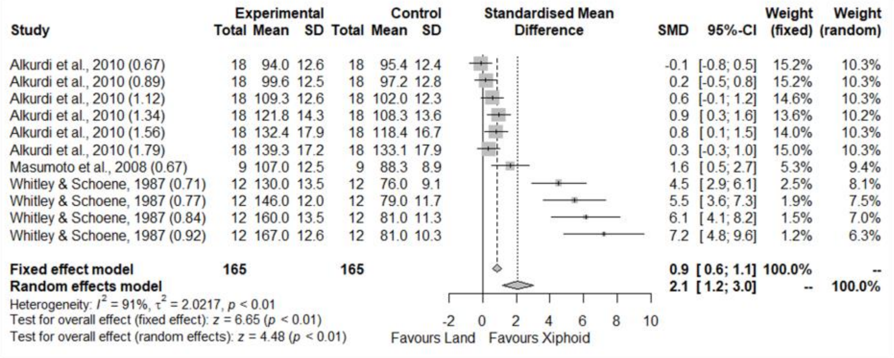
The HR was higher in SWW at waist depth than DLW at even walking speed (SMD: 3.22; 95%CI: 2.14 to 4.31; $p < 0.01$; I^2: 90%; 111.2 ± 21.1 vs. 91.1 ± 12.6 bpm) (Figure 12.B).

Rating of perceived exertion

The RPE for breathing (6 to 20 scale) was higher in SWW than in DLW at both xiphoid depths (SMD: 1.4; 95%CI: 0.7 to 2.0; $p < 0.01$; I^2: 54%; 11 ± 1 vs. 10 ± 1) (Figure 12.C) and waist depths (SMD: 0.83; 95%CI: 0.34 to 1.32; $p < 0.01$; I^2: 41%; 11 ± 2 vs. 9 ± 1) (Figure 12.D) at even walking speed.

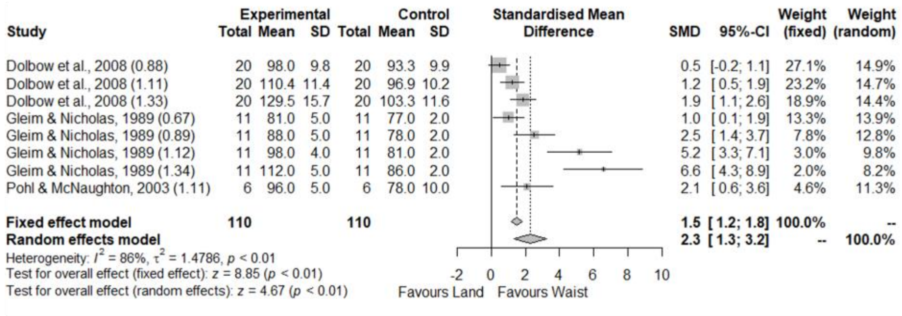
The RPE for lower limbs (6 to 20 scale) was higher in SWW at xiphoid depth than DLW at even walking speed (SMD: 3.0; 95%CI: 1.8 to 4.2; $p < 0.01$; I^2: 77%; 12 ± 2 vs. 10 ± 1) (Figure 12.E).

A. Heart rate: xiphoid depth vs. dry land



	Experimental			Control						
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Alkurdi et al., 2010 (0.67)	18	94.0	12.6	18	95.4	12.4	-0.1	[-0.8; 0.5]	15.2%	10.3%
Alkurdi et al., 2010 (0.89)	18	99.6	12.5	18	97.2	12.8	0.2	[-0.5; 0.8]	15.2%	10.3%
Alkurdi et al., 2010 (1.12)	18	109.3	12.6	18	102.0	12.3	0.6	[-0.1; 1.2]	14.6%	10.3%
Alkurdi et al., 2010 (1.34)	18	121.8	14.3	18	108.3	13.6	0.9	[0.3; 1.6]	13.6%	10.2%
Alkurdi et al., 2010 (1.56)	18	132.4	17.9	18	118.4	16.7	0.8	[0.1; 1.5]	14.0%	10.3%
Alkurdi et al., 2010 (1.79)	18	139.3	17.2	18	133.1	17.9	0.3	[-0.3; 1.0]	15.0%	10.3%
Masumoto et al., 2008 (0.67)	9	107.0	12.5	9	88.3	8.9	1.6	[0.5; 2.7]	5.3%	9.4%
Whitley & Schoene, 1987 (0.71)	12	130.0	13.5	12	76.0	9.1	4.5	[2.9; 6.1]	2.5%	8.1%
Whitley & Schoene, 1987 (0.77)	12	146.0	12.0	12	79.0	11.7	5.5	[3.6; 7.3]	1.9%	7.5%
Whitley & Schoene, 1987 (0.84)	12	160.0	13.5	12	81.0	11.3	6.1	[4.1; 8.2]	1.5%	7.0%
Whitley & Schoene, 1987 (0.92)	12	167.0	12.6	12	81.0	10.3	7.2	[4.8; 9.6]	1.2%	6.3%
Fixed effect model	**165**			**165**			**0.9**	**[0.6; 1.1]**	**100.0%**	--
Random effects model							**2.1**	**[1.2; 3.0]**	--	**100.0%**

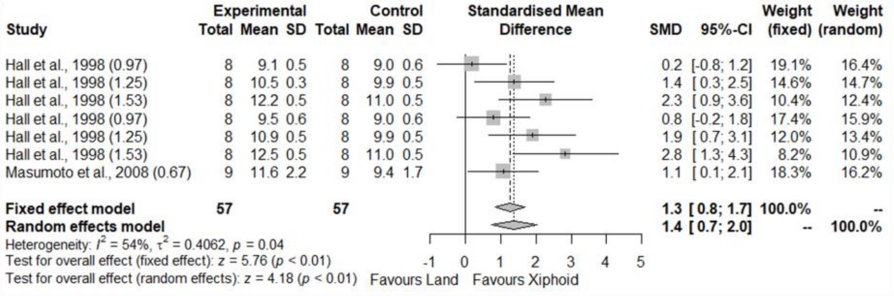
Heterogeneity: $I^2 = 91\%$, $\tau^2 = 2.0217$, $p < 0.01$
Test for overall effect (fixed effect): $z = 6.65$ ($p < 0.01$)
Test for overall effect (random effects): $z = 4.48$ ($p < 0.01$)



	Experimental			Control						
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Dolbow et al., 2008 (0.88)	20	98.0	9.8	20	93.3	9.9	0.5	[-0.2; 1.1]	27.1%	14.9%
Dolbow et al., 2008 (1.11)	20	110.4	11.4	20	96.9	10.2	1.2	[0.5; 1.9]	23.2%	14.7%
Dolbow et al., 2008 (1.33)	20	129.5	15.7	20	103.3	11.6	1.9	[1.1; 2.6]	18.9%	14.4%
Gleim & Nicholas, 1989 (0.67)	11	81.0	5.0	11	77.0	2.0	1.0	[0.1; 1.9]	13.3%	13.9%
Gleim & Nicholas, 1989 (0.89)	11	88.0	5.0	11	78.0	2.0	2.5	[1.4; 3.7]	7.8%	12.8%
Gleim & Nicholas, 1989 (1.12)	11	98.0	4.0	11	81.0	2.0	5.2	[3.3; 7.1]	3.0%	9.8%
Gleim & Nicholas, 1989 (1.34)	11	112.0	5.0	11	86.0	2.0	6.6	[4.3; 8.9]	2.0%	8.2%
Pohl & McNaughton, 2003 (1.11)	6	96.0	5.0	6	78.0	10.0	2.1	[0.6; 3.6]	4.6%	11.3%
Fixed effect model	**110**			**110**			**1.5**	**[1.2; 1.8]**	**100.0%**	--
Random effects model							**2.3**	**[1.3; 3.2]**	--	**100.0%**

Heterogeneity: $I^2 = 86\%$, $\tau^2 = 1.4786$, $p < 0.01$
Test for overall effect (fixed effect): $z = 8.85$ ($p < 0.01$)
Test for overall effect (random effects): $z = 4.67$ ($p < 0.01$)

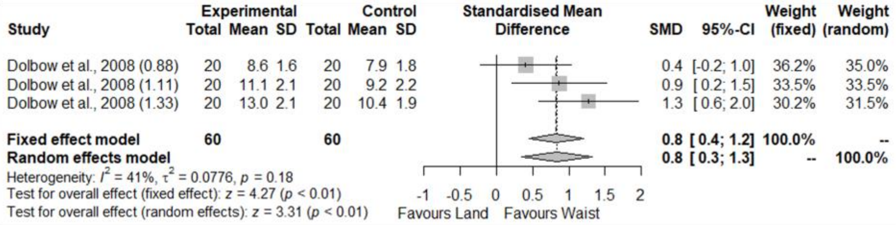
C. Breathing rating of perceived exertion: xiphoid depth vs. dry land



	Experimental			Control						
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Hall et al., 1998 (0.97)	8	9.1	0.5	8	9.0	0.6	0.2	[-0.8; 1.2]	19.1%	16.4%
Hall et al., 1998 (1.25)	8	10.5	0.3	8	9.9	0.5	1.4	[0.3; 2.5]	14.6%	14.7%
Hall et al., 1998 (1.53)	8	12.2	0.5	8	11.0	0.5	2.3	[0.9; 3.6]	10.4%	12.4%
Hall et al., 1998 (0.97)	8	9.5	0.6	8	9.0	0.6	0.8	[-0.2; 1.8]	17.4%	15.9%
Hall et al., 1998 (1.25)	8	10.9	0.5	8	9.9	0.5	1.9	[0.7; 3.1]	12.0%	13.4%
Hall et al., 1998 (1.53)	8	12.5	0.5	8	11.0	0.5	2.8	[1.3; 4.3]	8.2%	10.9%
Masumoto et al., 2008 (0.67)	9	11.6	2.2	9	9.4	1.7	1.1	[0.1; 2.1]	18.3%	16.2%
Fixed effect model	**57**			**57**			**1.3**	**[0.8; 1.7]**	**100.0%**	--
Random effects model							**1.4**	**[0.7; 2.0]**	--	**100.0%**

Heterogeneity: $I^2 = 54\%$, $\tau^2 = 0.4062$, $p = 0.04$
Test for overall effect (fixed effect): $z = 5.76$ ($p < 0.01$)
Test for overall effect (random effects): $z = 4.18$ ($p < 0.01$)

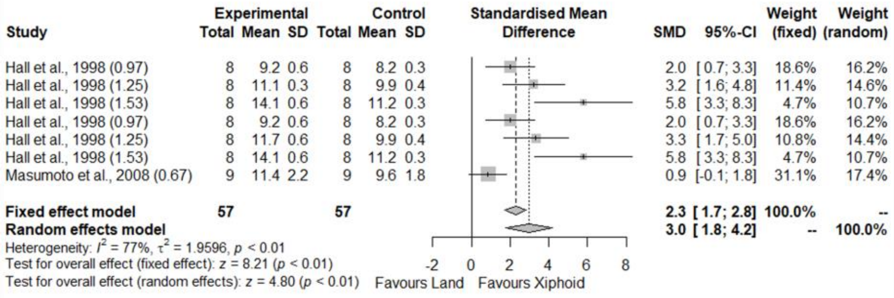
D. Breathing rating of perceived exertion: waist depth vs. dry land



	Experimental			Control						
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Dolbow et al., 2008 (0.88)	20	8.6	1.6	20	7.9	1.8	0.4	[-0.2; 1.0]	36.2%	35.0%
Dolbow et al., 2008 (1.11)	20	11.1	2.1	20	9.2	2.2	0.9	[0.2; 1.5]	33.5%	33.5%
Dolbow et al., 2008 (1.33)	20	13.0	2.1	20	10.4	1.9	1.3	[0.6; 2.0]	30.2%	31.5%
Fixed effect model	**60**			**60**			**0.8**	**[0.4; 1.2]**	**100.0%**	--
Random effects model							**0.8**	**[0.3; 1.3]**	--	**100.0%**

Heterogeneity: $I^2 = 41\%$, $\tau^2 = 0.0776$, $p = 0.18$
Test for overall effect (fixed effect): $z = 4.27$ ($p < 0.01$)
Test for overall effect (random effects): $z = 3.31$ ($p < 0.01$)

E. Lower limb rating of perceived exertion: xiphoid depth vs. dry land



	Experimental			Control						
Study	Total	Mean	SD	Total	Mean	SD	SMD	95%-CI	Weight (fixed)	Weight (random)
Hall et al., 1998 (0.97)	8	9.2	0.6	8	8.2	0.3	2.0	[0.7; 3.3]	18.6%	16.2%
Hall et al., 1998 (1.25)	8	11.1	0.3	8	9.9	0.4	3.2	[1.6; 4.8]	11.4%	14.6%
Hall et al., 1998 (1.53)	8	14.1	0.6	8	11.2	0.3	5.8	[3.3; 8.3]	4.7%	10.7%
Hall et al., 1998 (0.97)	8	9.2	0.6	8	8.2	0.3	2.0	[0.7; 3.3]	18.6%	16.2%
Hall et al., 1998 (1.25)	8	11.7	0.6	8	9.9	0.4	3.3	[1.7; 5.0]	10.8%	14.4%
Hall et al., 1998 (1.53)	8	14.1	0.6	8	11.2	0.3	5.8	[3.3; 8.3]	4.7%	10.7%
Masumoto et al., 2008 (0.67)	9	11.4	2.2	9	9.6	1.8	0.9	[-0.1; 1.8]	31.1%	17.4%
Fixed effect model	**57**			**57**			**2.3**	**[1.7; 2.8]**	**100.0%**	--
Random effects model							**3.0**	**[1.8; 4.2]**	--	**100.0%**

Heterogeneity: $I^2 = 77\%$, $\tau^2 = 1.9596$, $p < 0.01$
Test for overall effect (fixed effect): $z = 8.21$ ($p < 0.01$)
Test for overall effect (random effects): $z = 4.80$ ($p < 0.01$)

Figure 12 – Panel of heart rate and rating of perceived exertion meta-analysis **A.** Meta-analysis of heart rate at even walking speed (xiphoid depth vs. dry land). Standard mean differences between walking in the same speed (1.03 ± 0.38 m/s). **B.** Meta-analysis of heart rate at even walking speed (waist depth vs. dry land). Standard mean differences between walking in the same speed (1.06 ± 0.23 m/s). **C.** Meta-analysis of rating of perceived exertion for breathing at even walking speed (xiphoid depth vs. dry land). Standard mean differences between walking in the same speed (1.17 ± 0.32 m/s). **D.** Meta-analysis of rating of perceived exertion for breathing at even walking speed (waist depth vs. dry land). Standard mean differences between walking in the same speed (1.11 ± 0.23 m/s). **E.** Meta-analysis of rating of perceived exertion for lower limb at fixed speed (xiphoid depth vs. dry land). Standard mean differences between walking in the same speed (1.17 ± 0.32 m/s).

Muscular activity

All 10 studies (3, 4, 38, 40, 48, 49, 51, 53, 54, 67) that analyzed EMG, monitored lower limb EMG, and 3 (3, 4, 49) analyzed trunk EMG. Two studies (48, 67) have compared the same walking speed (0.67 and 0.66 m/s, respectively) between water and dry land, and 7 studies (3, 4, 38, 40, 51, 53, 54) have compared the same self-selected walking condition between water and dry land. None meta-analysis was performed with EMG due to the heterogeneity of data presentation. Details about the EMG findings of each study are descripted below and in Table 3. Only the Miyoshi et al. (51) study is not detailed due to the lack of information.

Masumoto et al. (48) have found higher activity at xiphoid depth in comparison to dry land of vastus medialis (VM), rectus femoris (RF), (long head) biceps femoris (BF), and gastrocnemius lateralis (GL), and similar activity for tibialis anterior (TA) at 0.67 m/s. Likewise, Shono et al. (67) comparing also xiphoid depth with dry land walking at 0.66 m/s observed in water higher activity VM, BF and TA, and similar activity for RF and gastrocnemius medialis (GM).

At self-selected speed conditions, Kotani et al. (40) found at 0.5 m depth water walking in comparison to dry land higher EMG activity in water for RF, BF, TA and GM, and similar EMG activity for vastus lateralis (VL) and gluteus medius (GlMed). Nakazawa et al. (54) found at 1.0 m depth water walking in comparison to dry land higher EMG activity for gluteus maximus, BF and tensor fascia latae (TFL), and similar EMG activity for RF, VL, TA, and soleus (SOL). Kaneda et al. (38) found at 1.1 depth water walking in comparison to dry land lower EMG activity in water for SOL, and similar EMG activity for VL, RF, BF, TA, GM. Miyoshi et al. (53) found at axillar depth similar activity of RF and TA, and higher activity in water for BF and GM.

Masumoto et al. (49) compared the EMG activity of RA, paraspinal (Psp), GlMed, RF, VM, BF lateral head, TA, and GL during walking in water at xiphoid depth and in dry land at slow, moderate and hard intensity (0.5 vs 1.0; 0.67 vs. 1.33; 0.83 vs. 1.67 m/s, respectively). The water condition was evaluated without and with addition of a water flow at subject’s chest in opposite sense of walking speed. At slow intensity, all muscles presented lower activity in water. At moderate intensity, only TA presented similar activity in water and dry land. At hard intensity, only BF and TA presented similar activities in water and dry land. With the addition of water flow in opposite sense of walking speed, the BF have had higher activity with flow in comparison to without flow condition at slow intensity.

Table 3 - Summary of muscular activity results.

Study	Depth	Walking speed	Muscle												
			Psp	**RA**	**GlMax**	**GlMed**	**TFL**	**RF**	**VL**	**VM**	**BF**	**TA**	**GM**	**GL**	**SOL**
Barela & Duarte (2008)	Xiphoid	SSWS	↑ (End of contact; Swing)	↑ (Foot strike)			↑ (Swing)		↑ (Contact)		↑ (Contact)	↑ (Swing)	=		
Barela et al. (2006)	Xiphoid	SSWS	↑ (End of contact; Swing)	↑ (Foot strike)			↑ (Swing)		↑ (Contact)		↑ (Contact)	↑ (Swing)	=		
Kaneda et al. (2007)	1.1 m	SSWS						=	=		=	=	=		↓
Kotani et al. (2009)	0.5 m	SSWS				=		↑	=		↑	↑	↑		
Masumoto et al. (2004)	Xiphoid	Slow (0.5 vs. 1.0 m/s)	↓	↓		↓		↓		↓	↓	↓		↓	

		Moderate (0.67 vs. 1.33 m/s)	↓	↓		↓		↓		↓	↓	=		↓	
		Hard (0.83 vs. 1.67 m/s)	↓	↓		↓		↓		↓	=	=		↓	
Masumoto et al. (2008)	Xiphoid	0.67 m/s						↑		↑	↑	=		↑	
Miyoshi et al. (2004)	Axillar	SSWS						=			↑	=	↑		
Nakazawa et al. (1994)	1.0 m	SSWS			↑		↑	=	=		↑	=			=
Shono et al. (2007)	Xiphoid	0.66 m/s						=		↑	↑	↑	=		

The comparisons of muscular activity response are between shallow water walking in relation to dry land walking. .BF: *biceps femoris*; GL: *gastrocnemius lateralis*; GlMax: gluteus *maximus*; GlMed: *gluteus medius*; GM: *gastrocnemius medialis*; Psp: *paraspinal*; RA: *rectus abdominis*; RF*: rectus femoris*; SOL: *soleus*; SSWS: comfortable self-selected speed; TA: *tibialis anterior*; TFL: *tensor fasciae latae;* VL: *vastus lateralis*; VM: *vastus medialis*.

5.4 Discussion

The purpose of our study was to employ a systematic review of physiologic, spatiotemporal, angular, kinetic, and neuromuscular parameters of SWW in different depths performed by healthy adults and elderly. We intended, therefore, to analyze organismal physiologic variables, particularly energy expenditure, and possible biomechanical determinants involved in the SWW. The main findings (Figure 13) are that energy expenditure (PMet and C), HR and RPE are increased at both xiphoid and waist depths in comparison to DLW at even walking speed. While at self-selected speed condition there is a reduction at walking speed, stride length, stride frequency, duty factor, and ground reaction forces in SWW at xiphoid depth in comparison to DLW. Our study updates the literature review in comparison to Heywood et al (33) and Denning et al. (18) studies, and also, to our knowledge, this is the first systematic review to develop a meta-analysis comparing walking in different shallow water depths and in dry land.

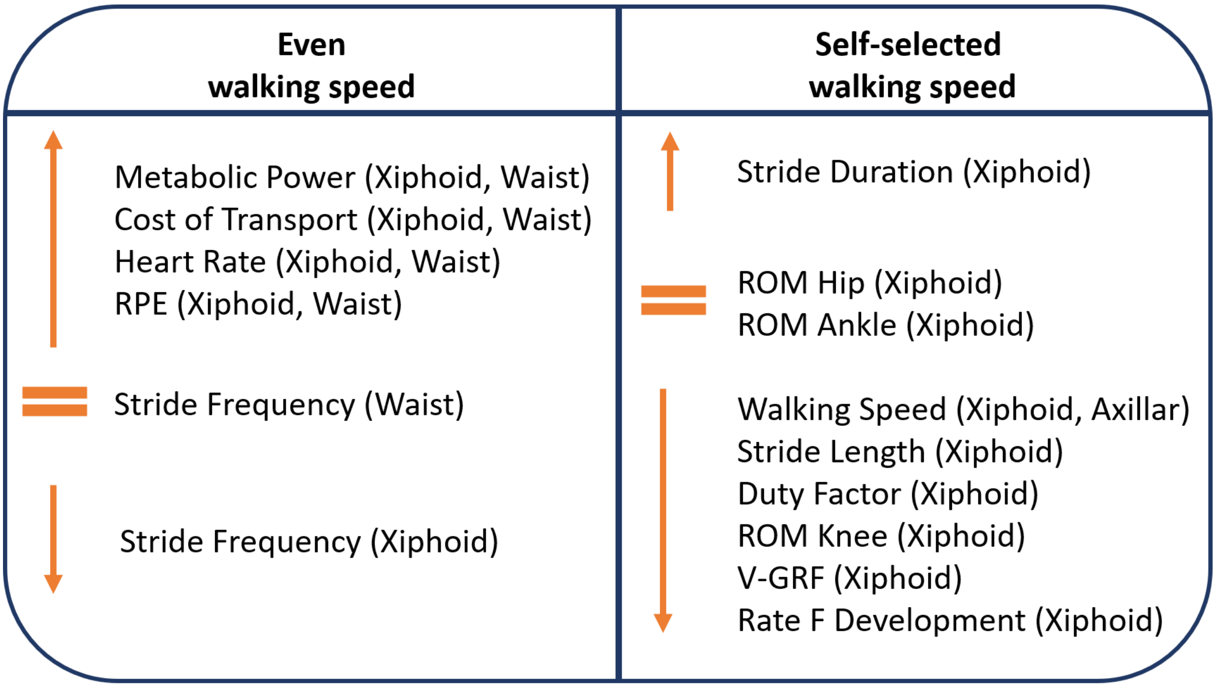


Figure 13 - Summary of meta-analysis results. All comparisons are made with dry land condition. F: force; ROM: range of motion; RPE: rating of perceived exertion (breathing and lower limb); V-GRF: vertical ground reaction force.

The higher physiologic demand during SWW in comparison to DLW at even walking speed could have some explanations. Firstly, one could analyze the hydrostatic force involved, and secondly, the hydrodynamic force.

The principal hydrostatic force acting during shallow water walking is the B that creates a simulated hypogravity condition. At simulated hypogravity there is a reduction of external mechanical work (14, 57), nevertheless, the metabolic demand does not diminish proportionally to the reduction of the mechanical demand (25, 29) or does not even diminish at all (57). Farley & McMahon (25) found a reduction of only 25% of C with a 75% reduction on gravity, while Pavei et al. (57) reported a non-statistically significant reduction of 18% in C at 0.36 and 0.16 g conditions. A possible explanation for this relatively high metabolic cost in simulated hypogravity conditions is the importance of the mechanical energy fluctuations of the moving limbs during walking (14, 29), i.e., internal mechanical work. Nevertheless, our findings do not demonstrate a relatively small reduction, but a significant increase in energy expenditure during SWW. Which take us to the hydrodynamic approach of the SWW.

At a given speed, there is a maintenance or increase of the stride frequency at dry land simulated hypogravity conditions with negligible DrF (14), but at SWW was observed a maintenance (waist depth) or decrease (xiphoid depth) of stride frequency at a fixed speed in comparison to DLW. Considering that the internal work is directly proportional to the stride frequency (13), one could expect that this maintenance/reduction of stride frequency would maintain/reduce the internal work, reducing the energy expenditure. The explanation of the higher physiologic demand during SWW in comparison to DLW - despite the expected reduction of both external and internal work at simulated hypogravity – can be the hydrodynamic resistance of water due the DrF. The DrF resists to the body displacement in the fluid, generating a mechanical dissipative system, breaking down the speed of locomotion. In order to maintain a constant speed, the body needs to employ extra chemical energy in order to overcome this resistance force during SWW, leading to higher physiologic demands (PMet, C, HR, RPE) and also modifying the spatiotemporal (stride frequency) characteristics of walking.

The HR was higher during SWW at even speed in comparison to DLW at both xiphoid and waist depths. Despite the bradycardia effect due to water immersion in rest condition (41), the walking activity was able to develop higher HR in water than in dry land when performed at even speed. Using the formula to calculate the predicted maximal HR during immersion proposed by Kruel et al. (41), it can be seen that SWW at xiphoid (127.9 ± 24.1 vs. 96.3 ± 18.1 bpm; 77% vs. 55% of maximum HR) and at waist (111.2 ± 21.1 vs. 91.1 ± 12.6 bpm; 63% vs. 49% of maximum HR) depths demands higher absolute and relative HR levels in comparison to DLW at the even speed. This higher HR could also help to explain the higher energy expenditure found for SWW due to reverse Fick principle (9) of oxygen consumption.

The RPE for breathing was higher at both waist and xiphoid depths than in DLW at even speed. Likewise, the RPE for lower limbs during walking at even speed was higher in xiphoid depth than in dry land. This could be related to the higher energy expenditure values encountered for walking at same speed in water in comparison to dry land. Also, the respiratory mechanical work is increased due to increased airways resistance and reduced pulmonary volume in aquatic immersion (1), probably affecting the breathing sensation.

During the self-selected condition, our results demonstrated a reduction of the comfortable (xiphoid and axillar) and fast (axillar) self-selected walking speed in SWW in comparison to DLW. In accordance with the principle of dynamic similarity, at hypogravity conditions the optimal walking speed is lower in comparison to Earth gravity, considering that the pendulum mechanism operates optimally at lower speeds of walking at lower gravity (45, 50, 58, 69). To maintain a constant Froude number of 0.25 - proportional to the optimal speed of walking – at hypogravity, the speed is reduced by a factor of the squared root from the relative gravity ($v_{new\ condition} = v_{Earth}(\sqrt{g_{new\ condition}/g_{Earth}})$). Therefore, the self-selected speed of walking, considered close to the optimal speed (64), would also be expected to be reduced in simulated hypogravity conditions.

The lower speed of walking in water in comparison to dry land could also be explained by a hydrodynamic approach. The DrF resists to the body displacement through the fluid and has a squared relation with the speed of displacement (71). Higher speed of walking causes higher DrF, inducing higher demands over the musculoskeletal system to sustain the motor activity. Masumoto et al. (46) found higher values of energy expenditure when walking at xiphoid depth in underwater treadmill with the addition of water flow on subject chest in opposite sense to walking speed, in comparison to a condition without the water flow. Therefore, at conditions that the subject is oriented to select the most comfortable speed of walking, it is expected lower speeds in water in comparison to dry land. This pattern seems to be independent of age (3, 4), gender (15), and water depth (4, 51, 53).

At self-selected speed condition, the SWW at xiphoid depth presented lower stride length (SMD = -1.38; 1.09 ± 0.18 vs. 1.28 ± 0.09 m) and higher stride duration (SMD: 6.40; 2.4 ± 0.4 vs. 1.0 ± 0.1 s) in comparison to DLW. Observing the higher SMD for stride duration, it seems that the walking speed reduction in water is mainly due to the temporal rather than spatial characteristics of gait cycle. This fact can also be explained by the hydrodynamic characteristics of the water walking: the reduction of walking self-selected speed in water seems to be caused mainly by the reduced angular velocity of the lower limb (17, 56) which will increment the stride period, more than due to reduction in the total foot excursion during the stride (stride length).

The lower limb ROM at self-selected speed showed similar values for hip and ankle, while knee presented lower values in SWW at xiphoid depth (SMD: -0.62; 55.6 ± 7.9 vs. 59.0 ± 6.6 º) in comparison to DLW. At first, these data suggest a somehow similar lower limb angular pattern for walking at xiphoid and dry land self-selected walking. Nevertheless, considering the reduced stride length in the xiphoid depth in comparison to dry land, one could expect reduced ROM at xiphoid condition. Modeling the lower limb as a pendulum with constant radium, a lower linear displacement (arch length) will cause a lower angular displacement; but this is not what happened for hip and ankle joints. So, we interpreted that although present similar absolute angular displacement at xiphoid depth and dry land, hip and ankle joints showed higher movement excursion at xiphoid depth. Similarly, the stride length is increased at major degree (SMD: -1.38) than knee ROM (SMD: -0.62).

The lower limb angular displacement adaptations during SWW can be a kinematic strategy to minimize the effects of DrF resistance. Considering the DrF dependence on the projected frontal area, the locomotor system seems to manage the DrF resistance by controlling the relative angular displacement of lower limb joints. In this way, the higher relative angular displacement could be a strategy to reduce the projected frontal area, considering the more flexed positions of hip (3, 10) and knee (3, 10, 17) during stride cycle. On the other side, the DrF dependence on speed seems to be controlled by the angular velocity. Despite the lower stride length during water walking, the similar absolute angular displacement associated with higher stride period leads to diminished peak angular velocities (17, 56).

The peak V-GRF and the rate of force development during walking at self-selected speed was lower in SWW at xiphoid depth than in DLW. The pattern of V-GRF curve during SWW was flatter in comparison to DLW (3, 4) at self-selected speed. The peak V-GRF was lower in water in comparison to dry land, even if the V-GRF was normalized by the body weight (11, 53, 54, 56) or by the apparent body weight in immersion condition (3, 4). This could be understood by the relation of peak V-GRF with both immersion ratio (ratio between water depth and stature) and speed of walking (32), considering the B effects and lower self-selected speed in water. The anterior-posterior ground reaction force curve during water walking assumed a predominant positive pattern, different from the negative-positive pattern of dry land walking (3, 4, 53, 56). This monophasic anterior-posterior ground reaction force curve is justified by the authors (4) as a kinetic strategy to maintain a constant walking speed and overcome the DrF horizontal resistance of water.

The muscular activity findings are not conclusive, but it can be observed a pattern of higher activity in SWW of lower limb in the studies that compared the same speed (48, 67) and self-selected speed (40, 53, 54) of walking in water and in dry land, what could be related to the necessity of overcome the DrF resistance in order to move the limb during gait cycle. The only study that reported a pattern of muscular activity reduction in water was of Masumoto et al. (49), but this study compared the SWW at half of the speed of the DLW at treadmill. Despite other studies compared self-selected speed between water and dry land – expected to be lower in water -, they analyzed shallow water walking on the pool floor, and not on an underwater treadmill (3, 4, 38, 40, 53, 54). The underwater treadmill condition can be a source of influence on the neuromuscular activation during walking, due to the reduced body center of mass horizontal displacement in comparison to the pool floor walking, that can reduce the force production demand from the neuromuscular system. And the other studies that investigated underwater treadmill have compared the muscular activity in SWW at same speed with DLW treadmill (48, 67). Also, at self-selected (3, 4, 40, 53, 54) and even (48, 67) speed of walking, BF activation was higher in SWW in comparison to DLW. This finding can be attributed to higher extensor hip moment observed during SWW, related to the need to overcome the DrF resistance (51–53).

Limitations

The limitations of this systematic review are related to the search terms choice and to language restriction, that could have left out others studies eligible to inclusion. The limitations associated with the analyses of the included studies are related to the methodological heterogeneity between studies, as the different depth method determination and speeds performed. Of all 40 included studies, only 7 (2, 27, 31, 37, 42, 54, 61) have used more than one depth as comparator to dry land, complicating a better understanding from the depth level influence on the walking parameters. The lack of information of the data results also have limited the inclusion of more studies in the meta-analysis.

Future investigations

Some suggestions can be made from the results of the present systematic review for future studies investigating the acute effects of SWW. It can be suggested the execution of studies that investigate more than one shallow water depth, in order to provide a better understand of the influence of hydrostatic and hydrodynamic forces involved during SWW on metabolic cost. For example, Kuliukas et al. (42) have found at waist depth walking higher values of C at low (<0.2 m/s) and high (>0.7 m/s) speeds, with the minimum C during walking at intermediate speeds (0.3 to 0.7 m/s). To our knowledge, this is the first study to demonstrate this C response during SWW. Nevertheless, remains the question if this U-shaped curve appears during walking in other depths.

A deeper exploration of the response of spatiotemporal (self-selected speed, stride frequency, stride length), lower limb angular parameters and neuromuscular activity during shallow water walking in other depths than xiphoid is recommended. The investigation of neuromuscular activity in different depths can help to explain the higher energy expenditure at organismal level.

The analysis of these variables on a more thorough depth gradation could enhance the exercise and therapeutic prescription to a variety of healthy conditions and different populations, and help to understand if these alterations can maximize gains in metabolic economy and gait biomechanics after long-term SWW intervention.

5.5 Conclusion

The SSW is a locomotion condition strongly influenced by the hydrostatic and hydrodynamic forces due water immersion. Our systematic review found higher physiologic demand (energy expenditure, HR, RPE) in SWW at waist and xiphoid depths in comparison to DLW at even walking speed. While at self-selected speed conditions was found lower speed, lower stride length, and lower stride frequency in SWW at xiphoid in comparison to DLW. All ground reaction forces were reduced during SSW, and muscular activity seems to be higher in water at even walking speed than dry land, or during floor walking at self-selected speed.

We recommend future studies exploring these physiological and biomechanical variables during SSW in other depths than xiphoid, in order to investigate if the neuromuscular activity can help to explain the higher energy expenditure at organismal level. Also, we indicate future studies that analyze if these alterations can maximize gains in metabolic economy and gait biomechanics after long-term SWW intervention.

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6. Study 2: Mechanical determinants from minimum cost of transport of shallow water walking in humans

Abstract

Although the physiologic and biomechanical responses of shallow water walking (SWW) have been studied extensively, a physiomechanical model aiming to define the mechanical determinants of cost of transport (C) of SWW is lacking. Therefore, the aims of this study were 1) to compare the C and the spatiotemporal parameters during SWW at different depths and speeds by healthy adult men, and 2) to propose a physiomechanical model called “water immersed inverted pendulum”, estimating the buoyancy force (B) and the drag force (DrF). We measured the C and spatiotemporal parameters at four depths (knee, hip, umbilical, xiphoid) and five speeds (0.2, 0.4, 0.6, 0.8 m/s, and at comfortable self-selected speed) in nine healthy adult men (28 ± 8 years, 77.7 ± 9.2 kg, 1.78 ± 0.04 m) during SWW. The C had a minimal value at intermediary speeds only in the knee depth, whilst in the other deeper depths the C presented a monotonic rise with the speed increase. A minimum C was found at hip depth during 0.2 m/s, suggesting an optimization between the effects of buoyancy and drag forces at this condition. The novel physiomechanical model allowed us to observe that the C in SWW seems be an optimized interplay between buoyancy and drag forces.

Key-words: locomotion; physiomechanics; aquatic walking; water immersion.

6.1 Introduction

Exercise in aquatic environment is a feasible and recommended intervention to a wide range of populations, being advantageous to pain (4, 14, 39, 41), muscle strength (5, 6, 46, 48), mobility (14), equilibrium (49), flexibility (5, 46), cardiorespiratory capacity (46), functionality (5, 41, 48, 49). Among others physical activities performed in aquatic environment, there is the shallow water walking (SWW) (26, 44).

The human walking can be interpreted by a physiomechanical model of inverted pendulum that actuates to minimize the metabolic energy expenditure due to mechanical energy exchange during gait cycle (42). This inverted pendulum enables the interchange between potential gravitational and kinetic forward energies, and its function depends on both intrinsic and extrinsic factors (10, 13, 38). The reduction of gravity acceleration during dry land simulated hypogravity has effects on different aspects of inverted pendulum response, as cost of transport (C), spatiotemporal parameters, and mechanical energy fluctuations (12, 35, 36, 40).

During SWW the human body is under the greater effects of two forces in comparison to dry land walking: buoyancy (B) and drag (DrF) forces. The B is a vertical force that opposes the gravitational force effect, reducing the apparent body weight of an immersed body, simulating a hypogravity environment ($g < 1.0$) (33). The DrF is a hydrodynamic force that resists to the displacement of a body immersed in a fluid. The total DrF is composed by pressure DrF, frictional DrF, and wave DrF (45); but the pressure DrF seems to be the most important DrF type during SWW (30).

Several studies have studied different physiologic and biomechanical parameters from SWW (2, 3, 17, 34). However, we did not have find any study proposing a SWW physiomechanical model in the light of inverted pendulum mechanism, although Kuliukas, Milne and Fournier (25) have found a U-shaped like C curve at waist depth. Therefore, we had two main aims with the present study (one experimental and one theoretical aim): 1) Experimental: to compare the C and the spatiotemporal parameters during SWW at different depths and speeds in healthy adult men. 2) Theoretical: considering that the C mechanical determinants from SWW are unclear, our second aim was to propose a physiomechanical model called “water immersed inverted pendulum”, estimating the B and the DrF. Our hypotheses were: 1)

The C of SWW would have a minimal value at intermediary speeds. 2) The C response would be related to the interplay between B and DrF.

6.2 Methods

Participants

The sample size calculus with a *f* effect size of 0.31, an α of 0.05, and power of 0.9 resulted in a sample size of 8 (*GPower v*. 3.9.1.4, Düsseldorf University, Düsseldorf, Germany). Nine men (28 ± 8 years, 77.7 ± 9.2 kg, 1.78 ± 0.04 m) were analyzed during the walking at shallow water. All subjects were healthy, without any neurological or musculoskeletal condition that could impair their walking ability. This study was approved by the institutional ethics committee (project number: 37928 / Universidade Federal do Rio Grande do Sul, Brazil). All subjects were aware of the potential risks of the experimental protocol and gave their written informed consent. The project was registered at Open Society Foundations (DOI 10.17605/OSF.IO/JFYXN) (Annex 2).

Experimental protocol and data collection

The data collection occurred in two non-consecutive days, with one week of interval at least. The subject was asked to walk at four immersion depths (knee, hip, umbilical, xiphoid) at four fixed speeds (0.2, 0.4, 0.6, 0.8 m/s) and at SSWS (self-selected comfortable speed) in each depth. The depths and speeds order were randomized. The subjects performed the walking at two depths at each day of data collection, accomplishing the four depths in two days. Anthropometric data from lower limb and trunk measures of lengths and circumferences were obtained.

The walking protocol was performed in a pool of 16 x 6 m. The pool floor was fixed; therefore, the immersion depths are presented in metric scale for each depth condition with the respective mean and standard deviation (SD) in percentage from subjects' stature. Knee: 0.5 m, 0.28 ± 0.01 % from stature. Hip: 0.85 m, 0.48 ± 0.01 % from stature. Umbilical: 1.12 m, 0.63 ± 0.01 % from stature. Xiphoid:1.3 m, 0.73 ± 0.02 % from stature. The water temperature was of 27 – 30 ºC.

The walking speed was controlled by a timed audible stimulus and marked positions every 2.5 m on the border of the pool. In each fixed speed condition, the subject was instructed to perform the displacement from on marker to another accordingly to the audible stimulus synchronization. Only for the SSWS condition, the subject was asked choose freely the speed of walking.

The walking protocol was performed in a round trip mode. The subject performed a 5 m walking distance, then turned around 180º at each 5 m. In order to evaluate if this circular route would affect the energy expenditure, we performed a pilot study (n =2, 25 ± 0 years, 84.5 ± 4.9 kg, 1.80 ± 0.08 m) in a larger pool where the subjects could walk in 10 m distance before turn around and compared to the 5 m path. In this pilot, we have found a mean difference of 2% higher C in 5 m path in comparison to the 10 m path, therefore validating our experimental design.

Each walking speed was performed during 5 minutes with 3 to 5 minutes rest interval between each speed. The return to basal levels of heart rate (HR) and rating of perceived exertion (RPE) was a criterion for initiate the subsequent walking condition. The SSWS condition was collected during a 2 minutes interval, because no physiological measure was made.

To account for influence of water immersion on cardiovascular rest parameters, a larger interval time between different depths was given. If the subject has first performed the walking in a deeper depth (xiphoid, p.ex.), a 15 minutes interval was respected before initiate the walking in the following shallower depth (umbilical, p.ex.) (16).

The kinematic data was collected by a waterproof GoPro Hero 5 (GoPro Inc., San Matea, USA) at 60 Hz. The camera was positioned at 4 m distance of the subject during the walking, with the lens projected at 90º with the sagittal plane of the subject. The camera was at 0.6 m (hip, umbilical, xiphoid) and 0.5 m (knee) from the pool floor. Anatomical points in the subjects’ skin were marked with ink at the following position (18): the fifth metatarsal, calcaneus, lateral malleolus, femoral epicondyle, greater trochanter, lateral projection of umbilical, lateral projection of xiphoid. In order to calibrate the area of movement in metric scale, a rectangular calibrator of 2.1 x 1.6 m dimensions (with 0.10 m distances between each calibrator marker) was used.

The O_2 consumption and CO_2 production were collected by a K5 wearable metabolic system (COSMED, Rome, Italy) in breath by breath mode calibrated accordingly to manufacturer instructions. At each depth, the respiratory gases response in rest orthostatic posture were collected during a 5 min period. During the walking tests, the respiratory gases were collected during all the 5 min of walking, but only the last 2 min of the walking test was used for posterior analysis. The HR and RPE were collected just before the start and just after the end of each walking test. The HR in bpm was collected with a hear rate monitor Polar FT1 (Polar, Kempele, Finland), and the RPE with a 6-20 Borg's scale (8).

Data analysis

The videos recorded by GoPro were imported into SkillSpector v. 1.2.3 where the anatomical points were manually digitalized. Five strides per subject in each speed condition were analyzed with a total of 700 strides. The position by time array of each anatomical point were exported and processed in a MatLab routine (2012b, Mathworks Inc., Natick, Massachusetts, USA). The routine is available on-line (https://github.com/andreivaniskimello/Gait-Analysis). The kinematic data were low-pass filtered with a Butterworth filter 4-5 Hz, 2nd order. From the position per time curves, the speed per time curves were calculated by finite-difference Winter's technique (47). From this kinematic data, the spatiotemporal variables were calculated: speed of walking (m/s), stride length (SL) (m), stride frequency (SF) (Hz), and duty factor (%). The speed of walking was calculated in order to verify if the subjects were walking at the proposed speed for each condition.

The energy expenditure was estimated by indirect calorimetry from the K5 data (22, 37). The O_2 and CO_2 data was used to estimate the J/kg/min expenditure in each condition (rest and walking). This was considered the gross-PMet (J/kg/min). The net PMet (PMet) (J/kg/min) was calculated from the subtraction of gross-Pmet during the walking condition from the gross-PMet obtained during the rest condition of the respective depth. The C (J/kg/m) was obtained dividing PMet by walking speed.

“Water immersed inverted pendulum” theoretical model

The “water immersed inverted pendulum” theoretical model was developed from physiologic collected and kinetic estimated data during SWW. The physiologic data was C. The kinetic data was estimated from kinematic and anthropometric data collected experimentally. The kinetic variables were: DrF and mean vertical ground reaction force during stride cycle (mV-GRF).

The DrF (N) was estimated from the model of Orselli and Duarte (34) using anthropometric and kinematic data. From anthropometric data of segments circumferences and lengths, the lower limb and trunk segments were modeled as a conic frustum. From the kinematic data, the velocity and angular position of each segment was calculated. The angular position was used to determine the frontal projected area of segment. The strip theory was used to estimate the DrF. In this strip theory, each segment is divided in several thin strips. Then the DrF is calculated for each of this strip at each time point, and the total DrF for the segment is calculated from the sum of all the strips. The DrF was calculated during the contact and swing phase, and the sum of these two phases resulted in the total DrF of the full stride. The total DrF during the stride was used for the statistical analysis and “water immersed inverted pendulum” theoretical model.

For estimate the B effect of each walking condition, the mV-GRF (N) during the entire stride cycle was estimated by the apparent body weight in each immersion depth. Considering the along the entire stride cycle, the mV-GRF is equal to the subject weight (28), we calculated the apparent body weight (% of dry land weight) for each depth accounting for the B weight bearing reduction effect (24), and considered this value of apparent body weight as the mV-GRF of the stride.

The SSW “water immersed inverted pendulum” model has taken in account, therefore, the mean values of C, DrF and mV-GRF of each condition of depth and walking speed. From the mean values of C, DrF and mV-GRF, we performed polynomial regression with C as dependent variable and DrF and mV-GRF as independent variables.

In order to compare our data of SWW with the dry land simulated hypogravity walking regression polynomial from Pavei and Minetti (36), we converted the gravity acceleration (g) into metric scale of immersion depth (m) using the data from Kruel (24) of apparent weight reduction due B (Equation 6). From the immersion depth in metric scale (m) of the anatomical landmark depths of the present study, we estimated the apparent weight reduction using the data of Kruel (24), and considering this apparent weight reduction as a simulated hypogravity condition, i.e., a ratio of Earth gravity acceleration. We considered the metric scale (m) as equivalent of gravity acceleration (g) to utilize the Pavei and Minetti (36) function to plot a dry land simulated hypogravity surface. The depths analyzed have the gravity acceleration equivalents of 0.88 g for knee, 0.58 g for hip, 0.48 g for umbilical, 0.33 for xiphoid.

The polynomial regression and all graphics were made in Phyton language. The scripts are available on-line (https://github.com/andreivaniskimello/Graphics).

Equation 6 - Conversion from depth of water immersion (m) into gravity acceleration (g).

$$Depth\ in\ metric\ scale\ (m) \rightarrow Apparent\ body\ weight\ (\%\ real\ body\ weight) \\ \rightarrow Earth\ dry\ land\ acceleration\ gravity\ ratio\ (g)$$

Statistical analysis

The results are presented as mean, SD and 95% confidence interval (95% CI). The alpha level α = 0.05 was set for all analyses. Statistical analysis was performed in Statistical Package for Social Sciences v.26 (SPSS, Chicago, Illinois, USA).

A simple *t*-test was used to compare the speed of walking achieved by the subjects with the proposed speed condition. Generalized linear mixed model (GLMM) was used to compare the dependent variables (SL, SF, duty factor, C, PMet, DrF, HR, RPE) response on the different conditions of depth (knee, hip, umbilical, xiphoid), speed (0.2, 0.4, 0.6, 0.8), and their interactions (depth*speed). And GLMM was used to compare the mV-GRF between depths. A correlation was used to verify the relation between C with kinetic parameters (DrF and mV-GRF).

6.3 Results

The individual dataset is disponible on-line (DOI: 10.6084/m9.figshare.13221485).

Spatiotemporal

The Table 4 presents the mean speed achieved for each walking speed condition. With exception of 0.8 m/s walking speed condition at all depths and 0.4 m/s at xiphoid depth, the subjects were able the reach the proposed walking speed in all speed conditions.

Table 4 – Mean walking speed in each depth during shallow water walking. The comparisons are made respectively with the proposed walking speeds (m/s): 0.2, 0.4, 0.6, 0.8.

Depth	Speed (m/s)	Statistics (t value; df; p)
Knee	0.19 ± 0.02	-0.798; 7; p = 0.451
	0.39 ± 0.02	-1.155; 7; p = 0.286
	0.64 ± 0.06	-1.594; 7; p = 0.155
	0.72 ± 0.04*	-5.001; 7; p = 0.002
Hip	0.19 ± 0.02	-0.834; 6; p = 0.436
	0.40 ± 0.02	0.000; 6; p = 1.000
	0.59 ± 0.02	-0.757; 6; p = 0.104
	0.73 ± 0.20*	-8.990; 6; p < 0.001
Umbilical	0.21 ± 0.01	2.169; 5; p = 0.082
	0.43 ± 0.30	2.371; 5; p = 0.064
	0.64 ± 0.06	1.914; 6; p = 0.104
	0.76 ± 0.04*	-2.791; 6; p = 0.032
Xiphoid	0.19 ± 0.02	-0.916; 5; p = 0.402
	0.43 ± 0.04*	2.622; 6; p = 0.039
	0.58 ± 0.04	-1.283; 4; p = 0.269
	0.64 ± 0.03*	-11.241; 2; p = 0.008

Data are presented as mean and standard deviation. The statistics is a simple *t*-test comparing the mean value obtained with the proposed walking speeds (m/s) of: 0.2, 0.4, 0.6, 0.8. *: statistically significant difference.

The SF (Figure 14 and Table 5) decreased with increased depth (F(3, 32.7) = 7.0 p = 0.001), while increased with increased speed (F(3, 66.6) = 120.7; p < 0.001). Yet, a significant interaction of depth*speed was not found for SF (F(9, 70.7) = 0.4; p = 0.93).

The SL (Figure 14 and Table 5) increased with both increased depth (F(3, 36,6) = 9.5; p < 0.001) and speed (F(3, 70.5) = 116.9; p < 0.001). While a significant interaction of depth*speed was found (F(9, 73.6) = 2.1; p = 0.041).

The duty factor (Figure 14 and Table 5) decreased with both increased depth (F(3, 33.5) = 24.2; $p < 0.001$) and speed (F(3, 62.4) = 259.7; $p < 0.001$). And a significant interaction of depth*speed was not found (F(9, 65.1) = 0.5; $p = 0.88$).

Table 5 - Mean and 95% CI of spatiotemporal variables at different depths and different speeds of walking condition.

Variable	Depth / Speed	0.2 m/s	0.4 m/s	0.6 m/s	0.8 m/s
SF (Hz)	**Knee**	0.38 (0.33–0.44) $^{A / a}$	0.52 (0.46-0.57) $^{B / a}$	0.63 (0.58-0.69) $^{C / a}$	0.70 (0.65-0.75) $^{C / a}$
	Hip	0.34 (0.29-0.39) $^{A / a}$	0.47 (0.42-0.52) $^{B / a, b}$	0.57 (0.52-0.63) $^{C / a, b}$	0.63(0.57-0.68) $^{C / a, b}$
	Umbilical	0.30 (0.26-0.34) $^{A / a}$	0.39 (0.36-0.41) $^{B / b}$	0.50 (0.47-0.53) $^{C / b}$	0.54 (0.49-0.58) $^{C / b}$
	Xiphoid	0.30 (0.25-0.36) $^{A / a}$	0.42 (0.36-0.47) $^{B / a, b}$	0.55 (0.48-0.61) $^{C / a, b}$	0.61 (0.53-0.69) $^{C / a, b}$
SL (m)	**Knee**	0.53 (0.42-0.65) $^{A / a}$	0.76 (0.65-0.88) $^{B / a}$	0.94 (0.82-1.05) $^{C / a}$	1.05 (0.94-1.17) $^{C / a}$
	Hip	0.58 (0.46-0.70) $^{A / a}$	0.89 (0.77-1.01) $^{B / a, c}$	1.06 (0.94-1.17) $^{C / a}$	1.20 (1.08-1.31) $^{D / a}$
	Umbilical	0.73 (0.61-0.85) $^{A / a}$	1.10 (0.98-1.23) $^{B / b}$	1.30 (1.18-1.42) $^{C / b}$	1.44 (1.32-1.56) $^{D / b}$
	Xiphoid	0.67(0.54-0.79) $^{A / a}$	1.06 (0.94-1.18) $^{B / b, c}$	1.09 (0.96-1.22) $^{B / a, b}$	1.04 (0.87-1.20) $^{B / a}$
Duty factor (%)	**Knee**	76.0 (74.5-77.5) $^{A / a}$	67.4 (65.9-68.9) $^{B / a}$	64.4 (62.9-65.8) $^{C / a}$	63.0 (61.5-64.5) $^{C / a}$
	Hip	75.2 (73.6-76.8) $^{A / a}$	66.9 (65.3-68.5) $^{B / a}$	62.9 (61.3-64.5) $^{C / a, b}$	61.9 (60.3-63.4) $^{C / a, b}$
	Umbilical	74.5 (72.8-76.2) $^{A / a}$	64.8 (63.1-66.5) $^{B / a, c}$	60.3 (58.7-61.9) $^{C / b, c}$	59.1 (57.5-60.7) $^{C / b, c}$
	Xiphoid	71.0 (69.3-72.8) $^{A / b}$	62.0 (60.5-63.7) $^{B / b, c}$	57.6 (55.7-59.4) $^{C / c}$	56.7 (54.3-59.1) $^{C / c}$

SF: stride frequency. SL: stride length. The letters indicate the comparisons of *post hoc* tests: different uppercase letters indicate statistically significant difference between speeds; different lowercase letters indicate statistically significant difference between depths.

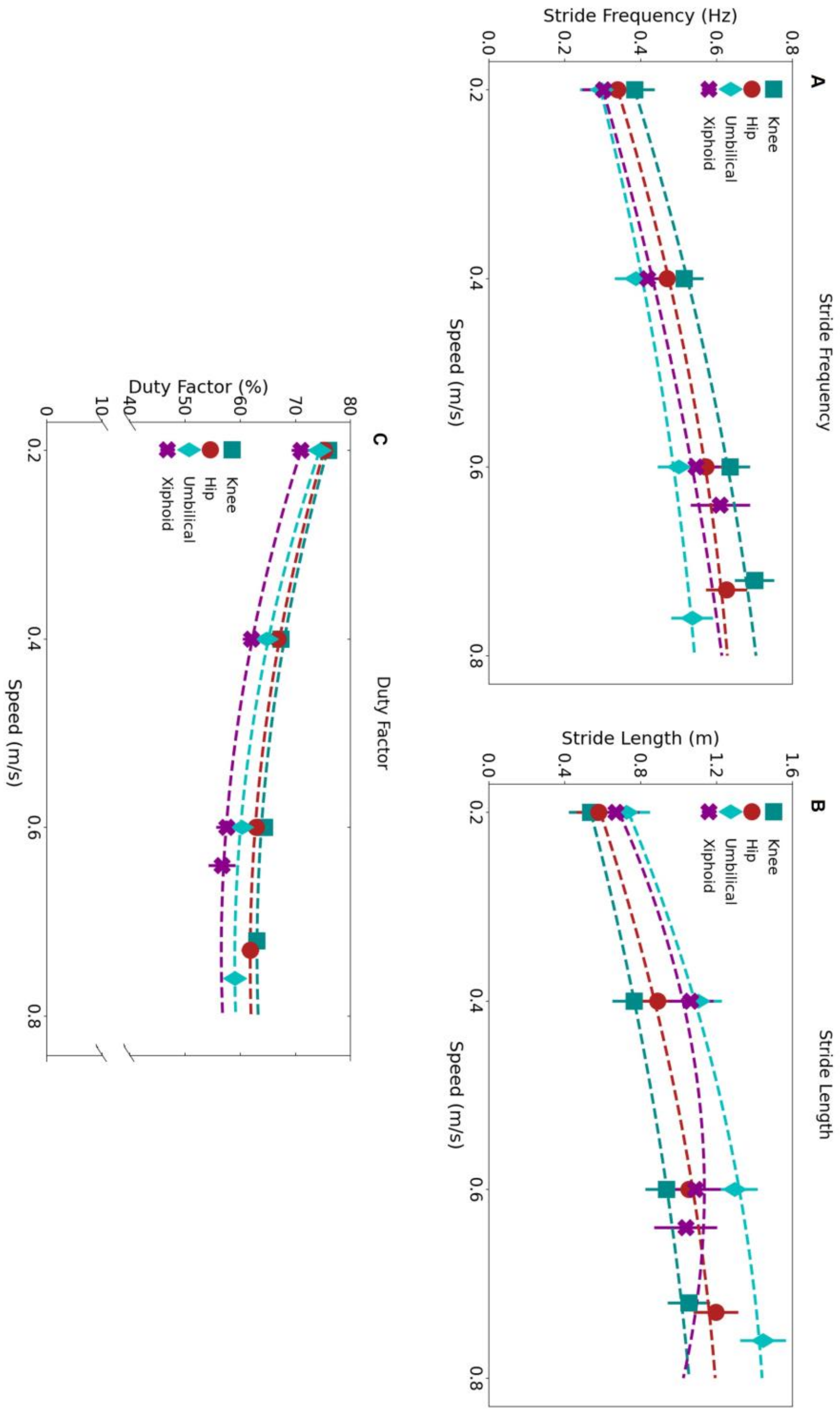

Figure 14 - Spatiotemporal variables per speed of walking condition at the different depths during shallow water walking: **A.** Stride frequency (Hz); **B.** Stride length (m); **C.** Duty factor (%). Values are presented as mean and 95% confidence interval. Squares are for knee deth. Circles are for hip depth. Diamonds are for umbilical depth. X is for xiphoid depth. The lines connecting each symbol are 2º order polynomial fit calculated for each depth calculated from experimental data. The lines' colors correspond to the respective depth symbol color.

Kinetic

The DrF increased with both increased depth (F(3, 45.1) = 30.4; $p < 0.001$) and speed (F(3, 77.0) = 403.0; $p < 0.001$); besides, a significant interaction of depth*speed was found (F(9, 77.8) = 17.6; $p < 0.001$). The mV-GRF decreased with increased depth (F(3, 150) = 439.0; $p < 0.001$) (Table 6).

Physiologic

The C (Figure 15) increased with both increased depth (F(3, 33.7) = 23.1; $p < 0.001$) and speed (F(3, 66.1) = 139.8; $p < 0.001$), furthermore a significant interaction of depth*speed was found (F(9, 69.2) = 10.9; $p < 0.001$). The PMet (Figure 16) increased with both increased depth (F(3, 29.7) = 25.0; $p < 0.001$) and speed (F(3, 61.5) = 344.1; $p < 0.001$), moreover a significant interaction of depth*speed was found (F(9, 65.6) = 16.2; $p < 0.001$) (Table 6).

Table 6 - Mean and 95% CI of physiologic and kinetic variables at different depths and different speeds of walking.

Variable	Depth / Speed	0.2 m/s	0.4 m/s	0.6 m/s	0.8 m/s
Cost of transport (J/kg/m)	**Knee**	2.7 (1.6-3.8) $^{A / a}$	2.8 (1.7-3.9) $^{A / a}$	3.3 (2.2-4.4) $^{A / a}$	4.4 (3.3-5.5) $^{A / a}$
	Hip	1.4 (0.19-2.5) $^{A / a}$	3.3 (2.1-4.5) $^{B / a}$	4.1 (3.0-5.3) $^{B / a}$	5.7 (4.6-6.8) $^{C / a}$
	Umbilical	2.8 (1.9-3.7) $^{A / a}$	4.7 (3.7-5.6) $^{B / a, b}$	7.3 (6.3-8.2) $^{C / b}$	9.6 (8.6-10.5) $^{D / b}$
	Xiphoid	2.7 (1.7-3.7) $^{A / a}$	5.9 (4.9-6.8) $^{B / b}$	9.5 (8.5-10.6) $^{C / c}$	12.7 (11.5-14.0) $^{D / c}$
Net metabolic power (J/kg/min)	**Knee**	32.7 (29.1-36.7) $^{A / a}$	68.1 (61.4-75.5) $^{B / a}$	118.8 (114.2-123.7) $^{C / a}$	212.6 (191.1-236.5) $^{D / a}$
	Hip	15.4 (11.8-20.0) $^{A / b}$	79.6 (65.2-97.1) $^{B / a, b}$	154.4 (140.9-169.1) $^{C / b}$	288.7 (267.5-311.5) $^{D / b}$
	Umbilical	33.1 (23.9-45.9) $^{A / a}$	111.7 (95.5-130.7) $^{B / b}$	260.9 (222.9-305.5) $^{C / c}$	458.7 (401.3-524.5) $^{D / c}$
	Xiphoid	32.3 (25.1-41.4) $^{A / a}$	140.9 (118.5-167.6) $^{B / c}$	351.5 (313.0-394.8) $^{C / d}$	579.6 (509.9-658.7) $^{D / c}$
Drag force (N)	**Knee**	8.7 (7.5-10.0) $^{A / a}$	22.0 (20.0-24.4) $^{B / a}$	38.6 (34.5-43.2) $^{C / a}$	58.7 (52.5-65.6) $^{D / a}$
	Hip	13.0 (11.2-15.0) $^{A / b}$	38.8 (35.6-42.3) $^{B / b}$	74.0 (68.5-80.0) $^{C / b}$	111.3 (103.6-119.5) $^{D / b}$
	Umbilical	20.9 (17.8-24.5) $^{A / c}$	67.1 (55.1-81.7) $^{B / c}$	115.9(96.6-139.0) $^{C / c}$	170.9(148.4-196.7) $^{D / c}$
	Xiphoid	18.9(16.4-21.8) $^{A / c}$	76.0(65.3-88.4) $^{B / c}$	133.9(111.5-160.9) $^{C / c}$	144.0(114.9-180.5) $^{C / b, c}$
GRFV * (N)	**Knee**	666.7(616.5-721.0) ^{a}			
	Hip	419.6(390.5-450.8) ^{b}			
	Umbilical	352.7(325.1-382.7) ^{c}			
	Xiphoid	244.7(221.6-267.8) ^{d}			

GRFV: mean vertical ground reaction force during the stride cycle. The letters indicate the comparisons of *post hoc* tests: different uppercase letters indicate statistically significant difference between speeds; different lowercase letters indicate statistically significant difference between depths. *****: Apparent body weight comparisons were only made between depths, without considering the different speeds of walking.

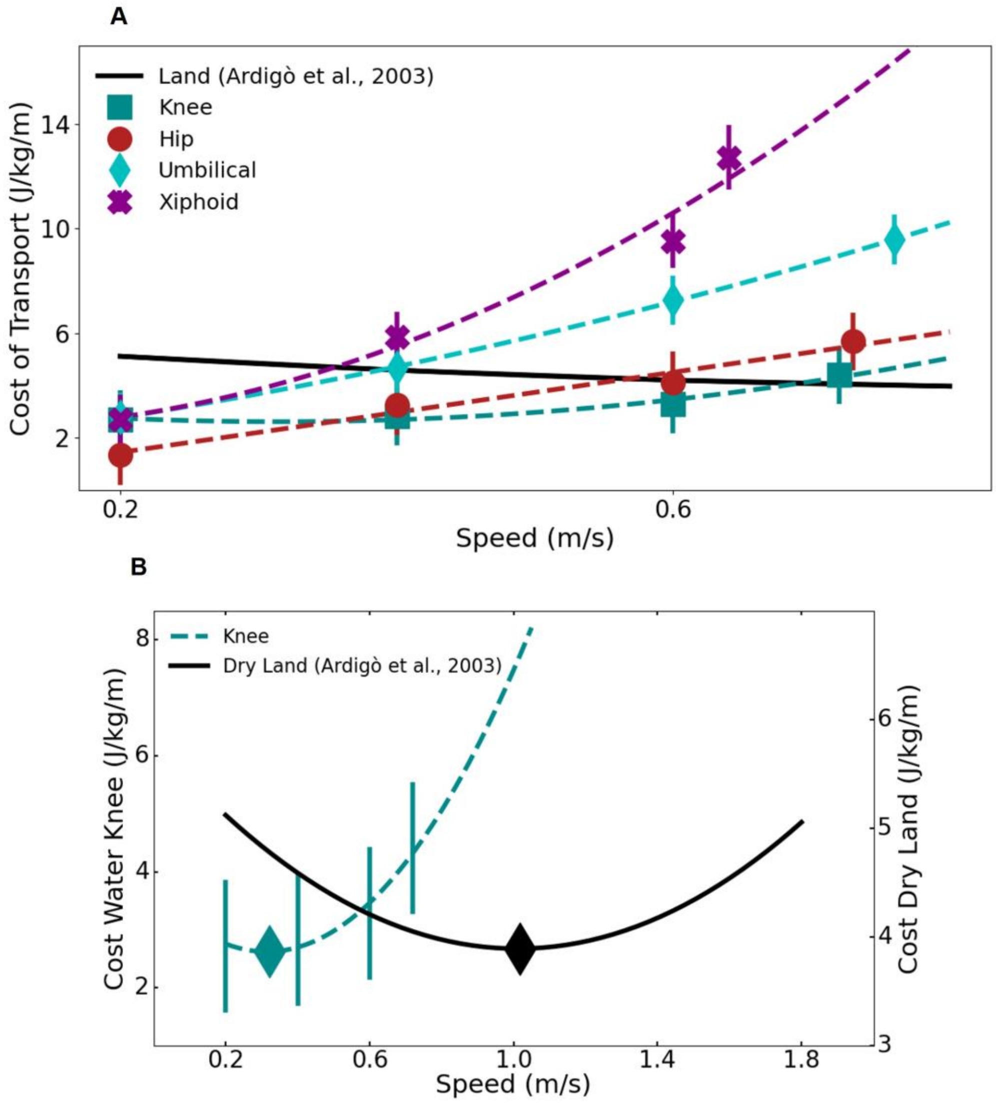

Figure 15 - Cost of transport (J/kg/m) per speed of walking (m/s) at different depths during shallow water walking in comparison to dry land walking. The data for shallow water walking was collected experimentally and 2º order polynomial fit curve for each depth was calculated, while the data for dry land walking (black line) are from a polynomial function by Ardigò, Saibene and Minetti (2003). **A.** All shallow water depths and dry land conditions are plotted. Knee: squares; hip: circles; umbilical: diamonds; xiphoid: xiphoid. The lines have the color corresponding to the respective depth symbol color. Values are presented as mean and 95% confidence interval. **B.** Only the knee depth is plotted in comparison to dry land, in order to demonstrated the U-shaped curve at this depth. The diamonds are the minimum points of cost of transport for each condition and have the color corresponding to the respective line color. The vertical blue bars crossing the blue knee depth line are the 95% confidence intervals for each speed condition obtained from experimental data.

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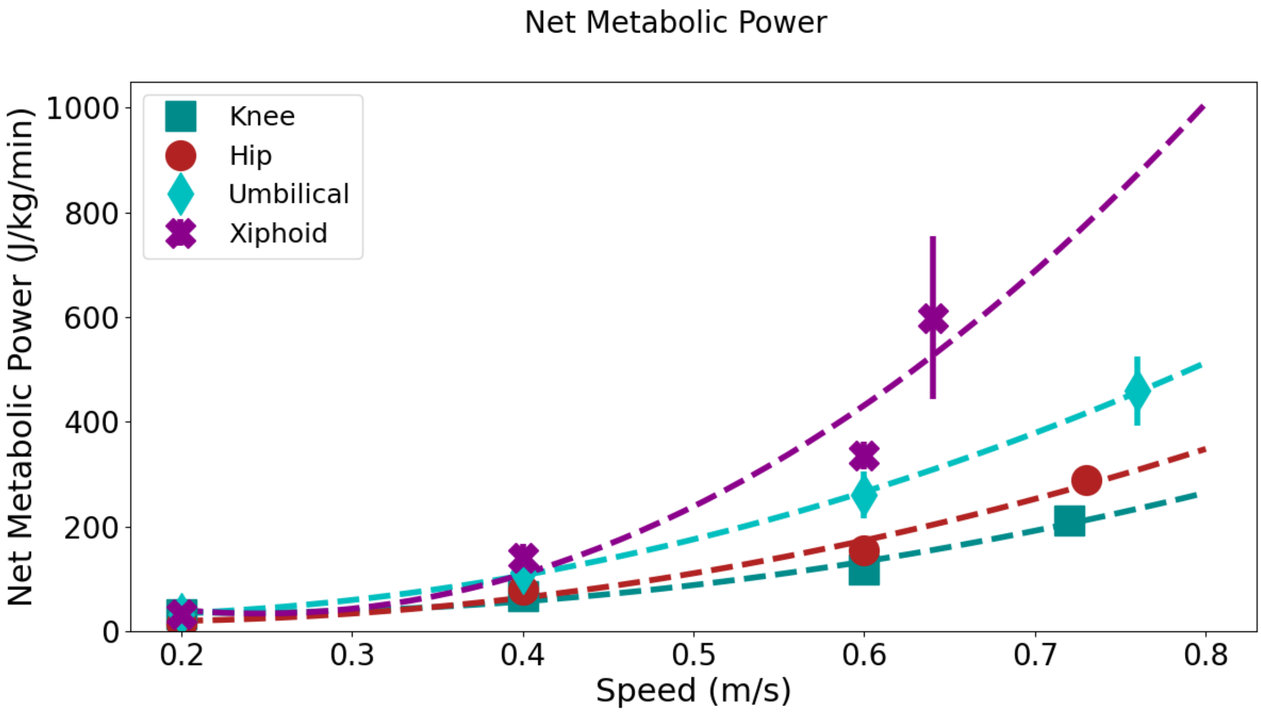

Figure 16 - Net metabolic power (J/kg/min) per speed of walking at the different depths during shallow water walking. Values are presented as mean and 95% confidence interval. Squares are for knee deth. Circles are for hip depth. Diamonds are for umbilical depth. X is for xiphoid depth. The lines connecting each symbol are 2º order polynomial fit calculated for each depth calculated from experimental data. The lines have the color corresponding to the respective depth symbol color.

What concerns the HR and the RPE response, both of them increased with increased depth (F(3, 42.7) = 3.2; p = 0.033; F(3, 41.0) = 5.7; p = 0.002, respectively) and speed (F(4, 104.2) = 123.5; p < 0.001; F(4, 100.1) = 184.0; p < 0.001, respectively). Also, a significant interaction of depth*speed was found for HR and RPE (F(12, 105.1) = 5.3; p < 0.001; F(12, 101.0) = 2.1; p = 0.024, respectively). For HR and RPE, the rest condition was compared as a speed condition (Table 7).

Table 7 - Mean and 95% CI of heart rate and rating of perceived exertion different depths and different speeds of walking.

Variable	Depth / Speed	Rest	0.2 m/s	0.4 m/s	0.6 m/s	0.8 m/s
Heart rate (bpm)	**Knee**	79 (71-87) $^{A, B / a}$	75 (68-83) $^{B / a}$	83 (75-91) $^{A, B / a}$	91 (83-99) $^{A / a}$	103 (95-111) $^{C / a}$
	Hip	79 (71-88) $^{A, B / a}$	75 (66-84) $^{A / a}$	84 (75-93) $^{A, B/ a}$	95 (86-104) $^{B/ a}$	119 (110-128) $^{C/ b}$
	Umbilical	74 (64-82) $^{A, B / a}$	74 (66-82) $^{B / a}$	87 (77-96) $^{A / a}$	107 (98-115) $^{C / a, b}$	135 (127-144) $^{D/b, c}$
	Xiphoid	70 (62-79) $^{A / a}$	71 (62-79) $^{A / a}$	93 (85-102) $^{B / a}$	114 (104-123) $^{C / b}$	148 (137-159) $^{D / c}$
RPE (6 – 20 scale)	**Knee**	6 (5-7) $^{A / a}$	7 (6-8) $^{A, B / a}$	8 (7-9) $^{B / a}$	10 (9-11) $^{C / a}$	13 (11-14) $^{D / a}$
	Hip	6 (5-8) $^{A / a}$	7 (6-8) $^{A / a}$	9 (8-10) $^{B / b}$	11 (10-12) $^{C / a, b}$	14 (13-15) $^{D / a, b}$
	Umbilical	6 (5-7) $^{A / a}$	7 (6-8) $^{A / a}$	10 (9-11) $^{B / b, c}$	11 (10-12) $^{B / a}$	15 (14-16) $^{C / b}$
	Xiphoid	7 (6-8) $^{A / a}$	8 (7-9) $^{A / a}$	10 (9-11) $^{B / c}$	13 (12-15) $^{C / b}$	16 (15-18) $^{D / b}$

RPE: rating of perceived exertion. The letters indicate the comparisons of *post hoc* tests: different uppercase letters indicate statistically significant difference between speeds; different lowercase letters indicate statistically significant difference between depths.

“Water immersed inverted pendulum” (physiomechanical model)

At Figure 15 are plotted regression curves showing the response of C in function of walking speed during SWW at different depths and at dry land walking. The SWW regression lines were calculated from experimental data, and the dry land walking line was extracted from the polynomial by Ardigò, Saibene and Minetti (1). The curves present inverted patterns for C x speed curve during SWW and dry land walking at slow speeds (until 0.8 m/s). While the C increases in water, the C decreases in dry land.

From the polynomial regression lines, we can observe isocost points between the SWW curves and dry land walking curve; that is, walking speeds at which the C is similar between SWW and dry land walking. The C is similar between dry land and SWW at the knee depth at 0.69 m/s with a C of 4.1 J/kg/m. And C is similar of dry land with SWW at hip depth at 0.59 m/s with 4.3 J/kg/m; with umbilical depth at 0.40 m/s with 4.66 J/kg/m; with xiphoid depth at 0.36 m/s with 4.78 J/kg/m. This could be interpreted as the points of metabolic equivalence between dry land walking and SWW. Also, one could observe that with the walking speed increase, the isocost points occurs at shallower depths.

The knee depth, however, presents a distinct pattern from the other depths. While all depths have presented a somewhat monotonic C increase accompanying the speed increase, the knee depth presented an U-shaped like curve (Figure 15.B). Nevertheless, when comparing with dry land curve minimum point (1.02 m/s; 3.89 J/kg/m), the knee depth had a minimum C (2.6 J/kg/m) at much lower walking speed of 0.32 m/s.

The correlation analysis showed a positive correlation of C with DrF ($r = 0.87$, $p < 0.001$), and negative correlation of C with mV-GRF ($r = -0.39$, $p < 0.001$). The response of C, DrF, and mV-GRF in different depths for each walking speed condition are presented in Figure 17.

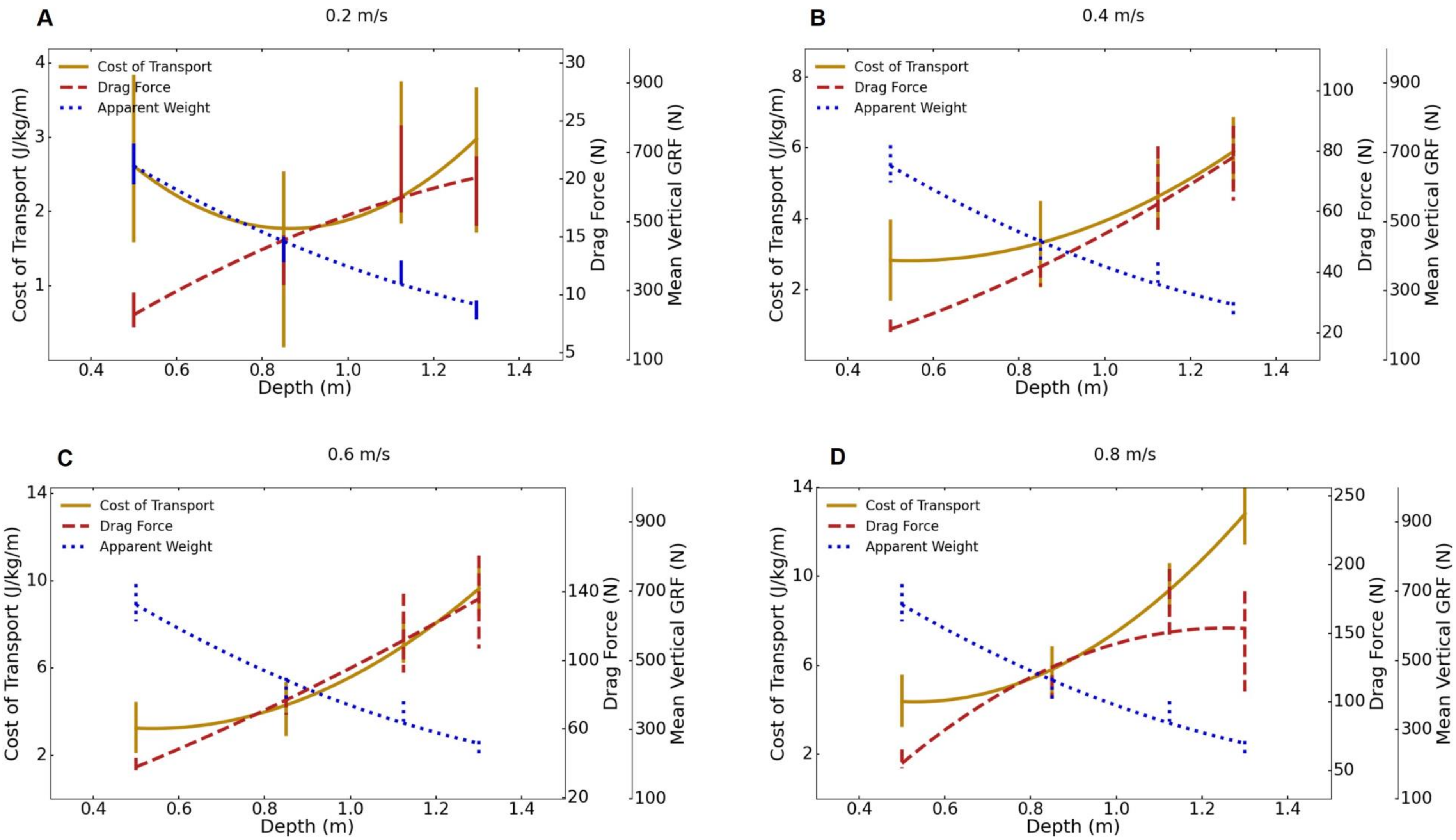
A
0.2 m/s
Cost of Transport
Drag Force
Apparent Weight
Cost of Transport (J/kg/m)
1
2
3
4
Drag Force (N)
5
10
15
20
25
30
Mean Vertical GRF (N)
100
300
500
700
900
Depth (m)
0.4
0.6
0.8
1.0
1.2
1.4
B
0.4 m/s
Cost of Transport
Drag Force
Apparent Weight
Cost of Transport (J/kg/m)
2
4
6
8
Drag Force (N)
20
40
60
80
100
Mean Vertical GRF (N)
100
300
500
700
900
Depth (m)
0.4
0.6
0.8
1.0
1.2
1.4
C
0.6 m/s
Cost of Transport
Drag Force
Apparent Weight
Cost of Transport (J/kg/m)
2
6
10
14
Drag Force (N)
20
60
100
140
Mean Vertical GRF (N)
100
300
500
700
900
Depth (m)
0.4
0.6
0.8
1.0
1.2
1.4
D
0.8 m/s
Cost of Transport
Drag Force
Apparent Weight
Cost of Transport (J/kg/m)
2
6
10
14
Drag Force (N)
50
100
150
200
250
Mean Vertical GRF (N)
100
300
500
700
900
Depth (m)
0.4
0.6
0.8
1.0
1.2
1.4

Figure 6 - Cost of transport (J/kg/m), drag force (N) and mean vertical ground reaction force (N) per depth of immersion (m) during shallow water walking at 0.2 m/s (**A**), 0.4 m/s (**B**), 0.6 m/s (**C**), 0.8 m/s (**D**) conditions. The lines are plotted from 2º order polynomial fit calculated for each variable from experimental data. The vertical bars crossing the lines are the 95% confidence intervals for each depth condition obtained from experimental data. Blue: mean vertical ground reaction force. Red: drag force Yellow: cost of transport.

The regression fit of C during SWW from walking speed and depth resulted in a 2º degree polynomial (Equation 7 and Figure 18).

Equation 7 - Cost of transport regression polynomial from immersion depth and walking speed.

$$\begin{aligned} Cost\ of\ Transport \\ &= (5.0 * Speed^2) + (11.3 * \ Depth^2) + (20.3 * Speed * Depth) \\ &- (13.0 * Speed) - (24.0 * Depth) + 12.5 \end{aligned}$$

The Table 8 presents the minimum and maximum values of C predicted by the surface regression models of SWW and dry land simulated hypogravity, with the respective values of depth and speed. The C values for SWW were estimated from the experimental data of the present study through Equation 7. While the C values for dry land simulated hypogravity were estimated from Pavei and Minetti (36) predictive equation. The correspondence between immersion depth (m) and gravitational acceleration (m/s^2) was detailed in Methods section (Equation 6).

Table 8 - Minimum and maximum values of cost of transport (J/kg/m) respective depth (m) and speed of walking (m/s) of each surface regression model (shallow water and dry land simulated hypogravity). Shallow water walking cost of transport were estimated from experimental data of the present study. Dy land simulated hypogravity cost of transport were estimated from Pavei and Minetti (36) predictive equation. Correspondence between water immersion depth (m) and gravitational acceleration (m/s^s) were determined from standing weight bearing reduction data from literature (Kruel, 1994).

Condition	**Surface model**	**Cost of transport (J/kg/m)**	**Depth (m)**	**Speed (m/s)**
Minimum	**Shallow water**	1.3	0.9	0.2
	Dry land simulated hypogravity	1.9	1.3	0.8
Maximum	**Shallow water**	14.3	1.3	0.8
	Dry land simulated hypogravity	3.0	0.5	0.2

Table 9 - Comfortable self-selected speed with respective cost of transport (estimated from polynomial regression surface) and Froude number. Values presented are the mean.

Depth condition	**Depth (m)**	**Speed (m/s)**	**Cost of transport (J/kg/m)**	**Froude number**
Knee	0.50	0.62	3.5	0.05
Hip	0.85	0.54	4.1	0.05
Umbilical	1.12	0.48	5.8	0.04
Xiphoid	1.30	0.44	7.0	0.05

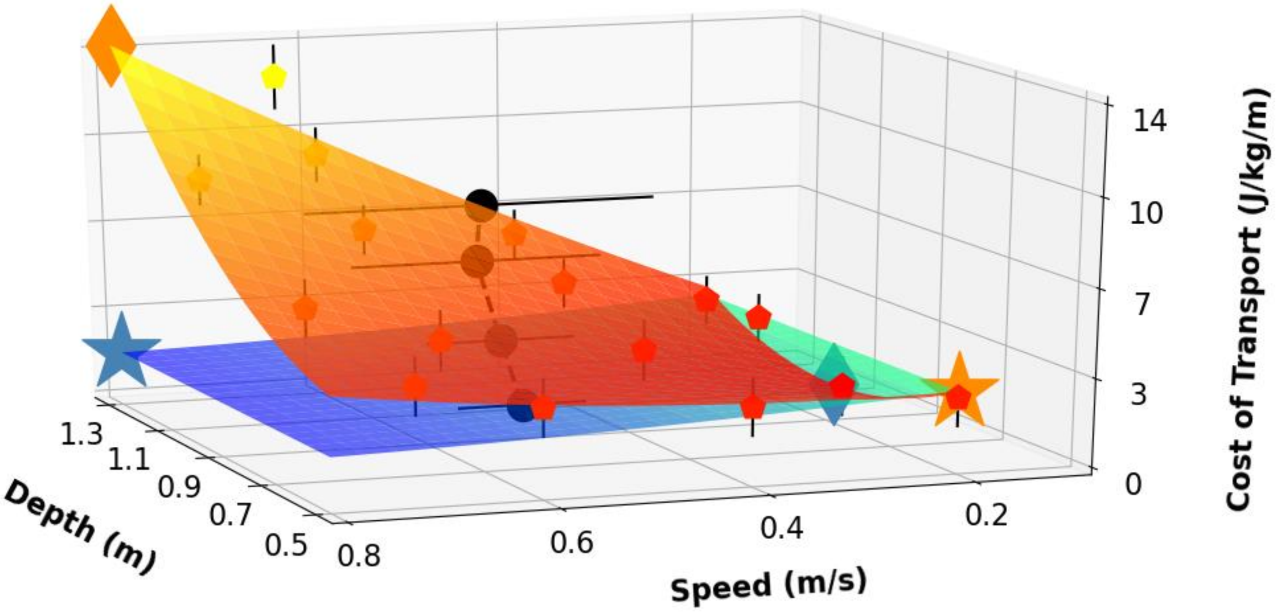

Figure 18 - Three-dimensional representation from cost of transport (J/kg/m) (mean and 95% confidence interval) per speed of walking (m/s) and depth of immersion (m) for shallow water (red) and dry land simulated hypogravity walking (blue). Surface regression plot from 2º order polynomial fit calculated from experimental data. A 360º view video from this plot in disponible online at https://doi.org/10.6084/m9.figshare.13012409.v1. **Red surface:** surface plot from 2º degree polynomial fit from experimental data of shallow water walking condition. **Blue surface:** surface plot from 2º degree polynomial fit from Pavei and Minetti (36) for dry land simulated hypogravity walking condition. The minimum (blue) and maximum (orange) points of cost of transport for each surface are represented as diamond (shallow water) and star (dry land simulated hypogravity). Black dots with line are the mean and 95% confidence interval of self-selected comfortable speed for each depth condition. A dashed line is ploted connecting each self-selected comfortable speed dot. For some points, the 95% confidence interval bar was minor than the symbol size.

6.4 Discussion

The aims of the present study were two-fold, one experimental and one theoretical. The former was to compare the C and spatiotemporal parameters during SWW at different depths and speeds in healthy adult men; while the latter was to propose a physiomechanical model called “water immersed inverted pendulum”, by estimating the B and DrF acting during SWW. Our first hypothesis was partially confirmed, as the C during SWW had a minimal value at intermediary speeds only in the knee depth, whilst in the other deeper depths the C presented a monotonic rise with the speed increase. Our second hypothesis that the C response in SWW would be related to the interplay between B and DrF was confirmed, as can it be better observed by the minimum C point at hip depth during 0.2 m/s speed, suggesting an optimization between the effects of B and DrF at this condition.

We observed higher energy expenditure (C and PMet), HR and RPE levels with the increase in both immersion depth and walking speed. At deeper depths, the body is on effect of a higher B, reducing the apparent body weight. Despite this reduced apparent body weight that could reduce the mechanical work needed to move the body center of mass (35), we observed higher energy expenditure. Although there is a C reduction during dry land simulated hypogravity walking (9, 15, 31, 32), it seems to be an uneven reduction between C and mechanical work at simulated hypogravity (19). This inequal decrease makes the dry land simulated hypogravity walking a locomotion type of relatively high C if normalized by the apparent body weight. Nevertheless, our results not only demonstrated an uneven reduction of C with weight bearing attenuation, but actually a C increase at higher immersion depths. This could be due to two factors: the altered function of inverted pendulum mechanism in reduced gravity and to the greater body frontal immersed in higher depths increasing the DrF resistance.

At simulated hypogravity walking, there are reports of an altered relation of the recovery of mechanical energy response and the speed of walking. That is, at an even walking speed, the authors have found lower recovery values at lower gravity, and the maximum value of recovery occurs at lower speed in lower gravity (12, 19, 35). Walking at even speed in deeper depths, therefore, could submit the inverted pendulum mechanism to function in a further point from an optimal condition, raising the necessity of higher C to walk. Also, at higher depths of immersion, a greater percentage of body area is immersed and under to water DrF resistance, increasing the muscular force production demand in order to maintain a constant speed of walking.

During walking in aquatic environment, the body is at a simulated hypogravity condition, but also under the effect of viscous resistance by water fluid. As our results demonstrated, the subjects’ body suffered higher DrF resistance at higher depths of immersion during even walking speed. Cavagna et al. (12) described two mechanical factors that decelerated the body in the forward direction during each step cycle during dry land simulated hypogravity: the gravity force during body lift and the ground impact at heel strike. Perhaps we could add to this model during shallow water simulated hypogravity conditions a third factor: the DrF resistance. For Cavagna et al. (12) the interplay between these two sources of forward velocity fluctuation affects the walking speed that occurs the maximum recovery (19, 35), and, consequently, the comfortable self-selected speed (42, 43). During SWW - a simulated hypogravity condition but with the addition of considerable DrF resistance - we observed this comfortable self-selected speed reduction with the immersion depth increase (lower gravity) but with an estimated increase of C (Table 9 and Figure 18).

In dry land simulated hypogravity conditions, occurs a reduction from the speed range that walking gait is possible. This speed range narrowing was predicted theoretically by the principle of dynamic similarity and also reported experimentally (11, 12, 23, 27, 29), and is attributed to the relation between the gravitational and inertial forces acting on body center of mass during walking. Nevertheless, despite the reduction from the absolute values of walking speed, the authors observed that both optimal and walk-to-run transition speeds occur at similar Froude number at different gravity conditions (23, 29). During SWW, we observed an important reduction of the Froude number of the self-selected speed in comparison to the 0.25 reported in the literature; besides, the Froude number for comfortable self-selected speed remained almost constant at all depths analyzed (0.04 - 0.05). This limitation of the self-selected speed - that in dry land is mainly due to the C (42) – at SWW could be related to a HR limiting factor in consequence of the DrF resistance, considering the overall similar HR between depths per speed (Table 9) with the exception for 0.8 m/s speed condition. However, this was the only speed condition that the subjects did not walk close to the goal speed (Table 4).

Our physiomechanical model of C response during SWW explained by the relation between hydrostatic B and hydrodynamic DrF shows a trend in the relation of SWW energy expenditure and the external forces involved (Figure 17). We could observe that with depth increase at all speeds the C curves increase in a similar trend along DrF despite of mV-GRF reduction. This response is corroborated by the higher correlation values of C with DrF than with mV-GRF (0.87 vs. -0.39, respectively). Therefore, it seems that for SWW the hydrodynamic characteristics of the task has more influence on the inverted pendulum response than the attenuation of gravitational force effects due to B. Another indication of this influence is the gap between the dry land simulated hypogravity C surface extracted from Pavei and Minetti (36) data and the SWW C surface developed from our experimental data (Figure 18). The gravity reduction of both surfaces was matched (apparent body weight), however it is visible the higher values of C for the water surface as the values of speed axis increase. We could also observe the similar minimum C values for both surfaces, but an almost 5 times higher maximum value in water in comparison to dry land simulated hypogravity (Table 5). Another relevant characteristic is the fact that dry land simulated hypogravity surface exhibits a typical U-shape pattern with the maximum C value appearing at 0.2 m/s, while the water surface has a more monotonic pattern with the minimum C at 0.2 m/s and the maximum at 0.8 m/s; response that could be attribute to the DrF resistance.

Despite the general trend of C rise accompanying the increase in both depth and speed, it is possible to observe a minimum point of C during SWW at hip depth at the 0.2 m/s. This could be interpreted in two ways: from a mechanical and from a physiological perspective.

In a mechanical view, we could account for an optimization of the relation between the DrF and apparent weight curves (Figure 17). At this depth point, occurs a reduction of the apparent weight that facilitate the work demand to move the body, while the magnitude of the DrF increase at this depth and speed is not enough to provide such important dynamic resistance to the body segments movement. Also, during 0.2 m/s walking speed the hip depth could be the point of optimal recovery mechanism owing to similar values of forward and vertical mechanical work (12) occurring at this simulated hypogravity condition. This optimal point of minimum C may not occur at other speeds as a result of the stronger resistance of DrF at higher speeds, or because the possible speed range where this optimal relation of forward and vertical mechanical work occurs is very reduced during SWW (close to 0.2 m/s).

While from a physiological view, we can observe that only at the hip depth occurred a reduction of the HR during 0.2 m/s walking in comparison to rest condition (Table 9), in spite of this reduction was not statistically significant. This HR reduction could be due a muscular pump from calf muscles activation during walking (2, 3), facilitating the vessel blood return, increasing final diastolic volume, and reducing HR by Frank-Starling mechanism (21). Finally, this HR reduction could have diminished the oxygen consumption by reverse Fick principle (7).

We also observed points of similar C (Figure 32) when comparing polynomial regression lines of SWW at different depths and dry land curve extracted from a polynomial by Ardigò, Saibene and Minetti (1). These points represent walking speeds at which the metabolic energy required to walk are similar in shallow water in comparison to dry land. The pattern of these isocost points shows that at higher immersion depths, lower the walking speed that has similar C during SWW and dry land walking; for comparison, the isocost point at 0.69 m/s at knee depth, and at 0.36 m/s at xiphoid depth. The isocost speed reduction with depth increase can be related to the higher DrF resistance experienced at deeper depths due to greater body volume immersed, requiring more metabolic energy to walk.

The U-shaped C curve appeared during SWW only in the regression polynomial from the shallower depth analyzed of knee (Figure 15), yet the minimum C point from knee curve was substantially dislocated to the left on the walking speed axis in comparison to dry land walking (0.32 vs. 1.02 m/s, respectively). Pavei, Biancardi and Minetti (35) have found the maintenance from the U-shaped curve during dry land simulated hypogravity walking at 0.36 and 0.16 g (Mars and Moon gravities); nevertheless, our results point that during SWW only at the depth closer to normogravity condition, i.e. knee with 0.88 g, the U-shaped curve seems to occur. Although the other depths had calculated higher gravity acceleration (0.58 g for hip, 0.48 g for umbilical, 0.33 for xiphoid) in comparison to the dry land simulated hypogravity conditions from Pavei, Biancardi and Minetti (35), the C curve at these deeper depths had always a constant positive slope. The DrF effect could account for this difference between SWW and dry land simulated hypogravity walking, generating important movement resistance, increasing monotonically the C with the speed increase.

The analysis from the minimum and maximum C values estimated for SWW and dry land simulated hypogravity walking (Table 5) demonstrated an opposite response for each condition in what concerns the walking speed. In SWW the minimum C point was at the speed of 0.2 m/s and the maximum at 0.8 m/s, while in dry land simulated hypogravity walking the minimum C occurred at 0.8 m/s and the maximum at 0.2 m/s. The predicted C values by polynomial regression was calculated for the walking speed range from 0.2 to 0.8 m/s, but we can still observe the predominant pattern of C increase accompanying the walking speed in SWW and the U-shaped curve for dry land. When observing the depths, the SWW had the minimum C point at 0.9 m and maximum C at 1.3 m; the dry land simulated hypogravity walking had a minimum at 1.3 m and maximum at 0.5 m. For SWW it seems to occur an optimization of the B and DrF at 0.9 m, appearing a valley for the C polynomial surface on this depth (Figure 18), while in dry land simulated hypogravity the gravitational effect appears to be predominant as the minimum C occurred in equivalent deeper depths.

The limitations of this study are the following: limited sample size; the speed control method that only allowed to know precisely if the subjects were walking at the goal speed during the data analysis stage; the DrF model was developed from 2D kinematic data, perhaps a 3D data could give more rich information about the DrF involved; the DrF model estimates only the pressure DrF, maybe a mathematical model that includes also the wave DrF and frictional DrF could improve the DrF resistance estimation; the pool floor was fixed, so the depth of immersion varied in a range around the anatomical landmark desired.

For future studies, we suggest the investigation of these parameters in other populations rather than healthy adult males, as females, older individuals, painful conditions, neuromuscular disorders, etc., in order to better understand the interplay between the mechanical forces and energy expenditure of shallow water walking. Also, we indicate the study of other depths than the utilized in this study, as ankle and shoulder, to give a more profound understand of the depth influence on this physiomechanical model. And the realization of longitudinal studies with the purpose to evaluate the effects of different physical interventions on these parameters is also encouraged.

6.5 Conclusion

Our results demonstrated that C had a minimal value at intermediary speeds only in the knee depth, and in the other deeper depths the C presented a monotonic rise with the speed increase. A minimum C point at hip depth during 0.2 m/s speed was found, suggesting an optimization between the effects of B and DrF at this condition. The C during SWW seems to be influenced by both depth and walking speed, what could be attributed to B and DrF, while the DrF seems to be a more important limiting factor to physiologic variables during SWW.

This is the first study to our knowledge to develop a SWW physiomechanical model using C measures and estimation from hydrostatic and hydrodynamic forces involved during SWW. Future studies testing this physiomechanical model in other depths, speeds, populations, and with an improved DrF estimation model are suggested.

6.6 References

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7.General conclusion

The general aim of this dissertation was to examine the shallow water walking effects on inverted pendulum mechanism through a physiomechanical of inverted pendulum response during shallow water walking by healthy adult men. We hypothesized that the inverted pendulum mechanism would be affected by the buoyancy and drag forces, and that would exist an optimal point of shallow water walking cost of transport due to the interplay between these forces (Figure 19).

To our knowledge, this is the first study to propose a physiomechanical model from shallow water walking. We have analyzed this “water immersed inverted pendulum” from the literature background about dry land simulated hypogravity walking. In shallow water walking in addition to this simulated hypogravity condition due to buoyancy force, the hydrodynamic resistance by drag force to movement is presented. The “water immersed inverted pendulum” would be, therefore, this free body diagram that takes in account both buoyancy and drag forces acting on an immersed inverted pendulum.

Our systematic review indicate that SSW is a locomotion condition strongly influenced by the hydrostatic and hydrodynamic forces due water immersion. Shallow water walking presented higher physiologic demand in shallow water walking at waist and xiphoid depths in comparison to dry land walking at even walking speed.

Concerning the physiomechanical model proposed here, the main finding is a minimum cost of transport cost at hip depth during the slowest walking speed analyzed (0.2 m/s), probably in consequence of the optimal interplay between buoyancy and drag forces at this condition. Also, the cost of transport had a minimal value at intermediary speeds only in the knee depth, resembling an U-shaped curve of cost of transport per speed; while in the other deeper depths the C presented a monotonic rise with the speed increase

The cost of transport during shallow water walking seems to be influenced by both depth and walking speed, what could be attributed to buoyancy and drag forces effects. Future studies testing this physiomechanical model in other depths, speeds, populations, and with an improved drag force estimation model are suggested.

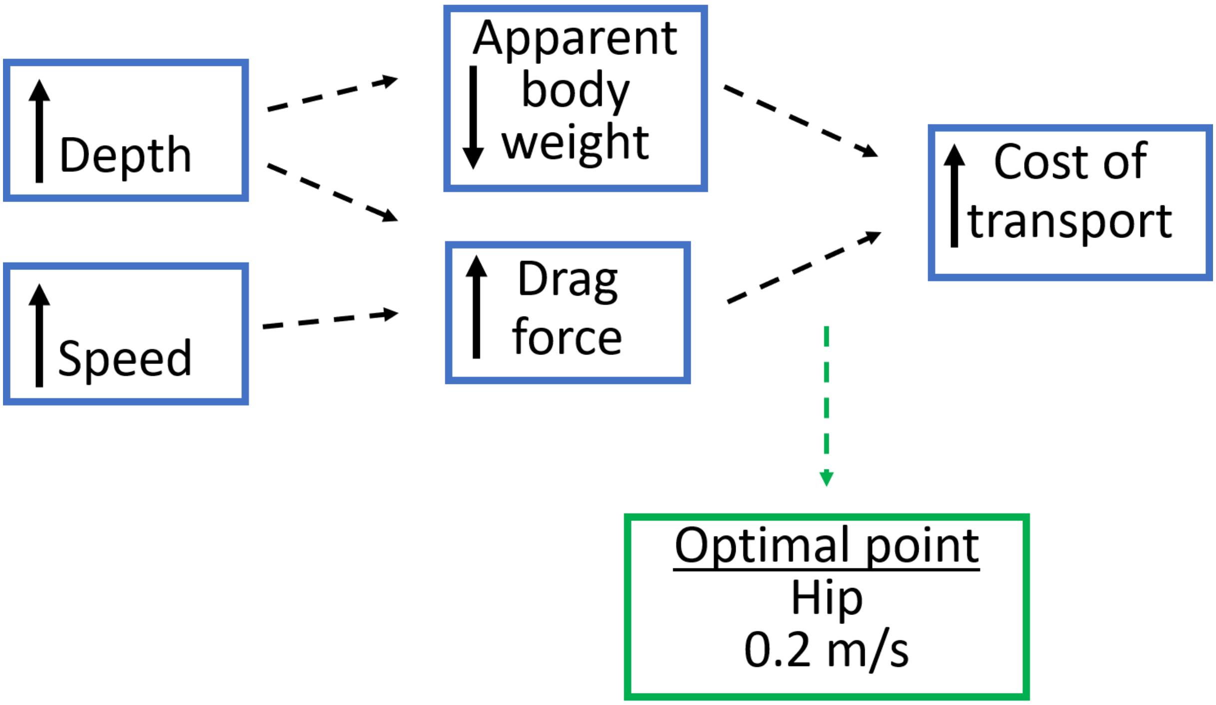

Figure 19 - Conceptual model for physiomechanics of shallow water walking.

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9. Annex

9.1. Annex 1 - Study 1 registry in PROSPERO

UNIVERSITY of York
Centre for Reviews and Dissemination

Systematic review

1. Review title.

Give the working title of the review, for example the one used for obtaining funding. Ideally the title should state succinctly the interventions or exposures being reviewed and the associated health or social problems.Where appropriate, the title should use the PI(E)COS structure to contain information on the Participants, Intervention (or Exposure) and Comparison groups, the Outcomes to be measured and Study designs to be included.

Gait parameters during shallow water walking in comparision with dry land walking by adults and elderly: asystematic review

2. Original language title.

For reviews in languages other than English, this field should be used to enter the title in the language of thereview. This will be displayed together with the English language title.

Parâmetros da marcha durante caminhada em água rasa comparada com caminhada no solo por adultos eidosos: revisão sistemática

3. Anticipated or actual start date.

Give the date when the systematic review commenced, or is expected to commence.22/10/2018

4. Anticipated completion date.

Give the date by which the review is expected to be completed.31/12/2018

5. Stage of review at time of this submission.

Indicate the stage of progress of the review by ticking the relevant Started and Completed boxes. Additionalinformation may be added in the free text box provided.

Please note: Reviews that have progressed beyond the point of completing data extraction at the time of initial registration are not eligible for inclusion in PROSPERO. Should evidence of incorrect status and/or completion date being supplied at the time of submission come to light, the content of the PROSPERO record will be removed leaving only the title and named contact details and a statement that inaccuracies inthe stage of the review date had been identified.

This field should be updated when any amendments are made to a published record and on completion andpublication of the review. If this field was pre-populated from the initial screening questions then you are notable to edit it until the record is published.

The review has not yet started: Yes

Review stage	Started	Completed
Preliminary searches	No	No
Piloting of the study selection process	No	No
Formal screening of search results against eligibility criteria	No	No
Data extraction	No	No
Risk of bias (quality) assessment	No	No
Data analysis	No	No

Provide any other relevant information about the stage of the review here (e.g. Funded proposal, protocol notyet finalised).

6. Named contact.

The named contact acts as the guarantor for the accuracy of the information presented in the register record.André Ivaniski Mello

Email salutation (e.g. "Dr Smith" or "Joanne") for correspondence:

Mr Ivaniski Mello

7. Named contact email.

Give the electronic mail address of the named contact.andreivaniskimello@gmail.com

8. Named contact address

Give the full postal address for the named contact.

Felizardo street, 750, Jardim Botânico, Porto Alegre, Rio Grande do Sul, BrazilPostal Zip: 90690-200

9. Named contact phone number.

Give the telephone number for the named contact, including international dialling code.55 51 993566876

10. Organisational affiliation of the review.

Full title of the organisational affiliations for this review and website address if available. This field may becompleted as 'None' if the review is not affiliated to any organisation.

Universidade Federal do Rio Grande do Sul

Organisation web address:

www.ufrgs.br

11. Review team members and their organisational affiliations.

Give the title, first name, last name and the organisational affiliations of each member of the review team.Affiliation refers to groups or organisations to which review team members belong.

Mr André Ivaniski Mello. Universidade Federal do Rio Grande do Sul

Ms Marcela Zimmermann Casal. Universidade Federal do Rio Grande do SulDr Rochelle Costa. Universidade Federal do Rio Grande do Sul

Dr Leonardo Alexandre Peyré Tartaruga. Universidade Federal do Rio Grande do SulDr Luiz Fernando Martins Kruel. Universidade Federal do Rio Grande do Sul

Dr Flávia Gomes Martinez. Universidade Federal do Rio Grande do Sul

12.* Funding sources/sponsors.

Give details of the individuals, organizations, groups or other legal entities who take responsibility for initiating, managing, sponsoring and/or financing the review. Include any unique identification numbersassigned to the review by the individuals or bodies listed.

None

13. Conflicts of interest.

List any conditions that could lead to actual or perceived undue influence on judgements concerning themain topic investigated in the review.

None

14. Collaborators.

Give the name and affiliation of any individuals or organisations who are working on the review but who arenot listed as review team members.

15. Review question.

State the question(s) to be addressed by the review, clearly and precisely. Review questions may be specificor broad. It may be appropriate to break very broad questions down into a series of related more specific questions. Questions may be framed or refined using PI(E)COS where relevant.

There are differences in gait parameters during shallow water walking in comparision with dry land walkingperformed by adults and elderly?

16. Searches.

Give details of the sources to be searched, search dates (from and to), and any restrictions (e.g. language orpublication period). The full search strategy is not required, but may be supplied as a link or attachment.

The sources that will be searched are: PubMed, EMBASE, Scopus, Pedro, and Cochrane Library. Will be accepted studies published until the search date. The search will be conducted without language limitations.(walk[tw] OR walking[MeSH] OR gait[MeSH]) AND (“water-based activities” [tw] OR “activities, water- based” [tw] OR “water aerobics” [tw] OR “aerobics, water” [tw] OR "water aerobic exercise" [tw] OR

"aerobic exercise, water" [tw] OR “water aerobic exercises” [tw] OR “aerobic exercises, water” [tw] OR“aquatics” [tw] OR “water walking” [tw] OR “walking, water” [tw] OR “shallow water walking” [tw] OR “walking, shallow water” [tw] OR “aquatic environment” [tw] OR “environment, aquatic” [tw] OR “underwater treadmill” [tw] OR “water treadmill” [tw] OR “aquatic treadmill” [tw] OR aquatic [tw] OR

water[MeSH] OR immersion[MeSH])

17. URL to search strategy.

Give a link to a published pdf/word document detailing either the search strategy or an example of a searchstrategy for a specific database if available (including the keywords that will be used in the search strategies), or upload your search strategy.Do NOT provide links to your search results.

Alternatively, upload your search strategy to CRD in pdf format. Please note that by doing so you are consenting to the file being made publicly accessible.

Do not make this file publicly available until the review is complete

18. Condition or domain being studied.

Give a short description of the disease, condition or healthcare domain being studied. This could includehealth and wellbeing outcomes.

Gait parameters.

19 Participants/population.

Give summary criteria for the participants or populations being studied by the review. The preferred formatincludes details of both inclusion and exclusion criteria.

Studies involving adults and elderly will be accepted.

20. Intervention(s), exposure(s).

Give full and clear descriptions or definitions of the nature of the interventions or the exposures to bereviewed.

Walking immersed in shallow water regardless of the depth.

21. Comparator(s)/control.

Where relevant, give details of the alternatives against which the main subject/topic of the review will be compared (e.g. another intervention or a non-exposed control group). The preferred format includes detailsof both inclusion and exclusion criteria.

Walking in dry land.

22. Types of study to be included.

Give details of the types of study (study designs) eligible for inclusion in the review. If there are no restrictions on the types of study design eligible for inclusion, or certain study types are excluded, this shouldbe stated. The preferred format includes details of both inclusion and exclusion criteria.

Observational and clinical trials (or interventional) studies will be included.

23. Context.

Give summary details of the setting and other relevant characteristics which help define the inclusion orexclusion criteria.

24. Main outcome(s).

Give the pre-specified main (most important) outcomes of the review, including details of how the outcome isdefined and measured and when these measurements are made, if these are part of the review inclusion criteria.

The following variables will be accepted:

Kinematic and spatiotemporal: articular range of movement, walking speed, cadence, step length, stride length, stride duration, stance time, assymmetry between limbsKinetics : ground reaction forces.

Mechanics: internal, external and total work, mechanical power, mechanical efficiency.

Neuromuscular: muscle activity.

Physiological: energy expenditure, energy cost, oxygen consumption, respiratoy-exchange ratio, minuteventilation, heart rate, blood pressure, rating of perceveid exertion.

25. Additional outcome(s).

List the pre-specified additional outcomes of the review, with a similar level of detail to that required for mainoutcomes. Where there are no additional outcomes please state ‘None’ or ‘Not applicable’ as appropriate to the review

None.

26. Data extraction (selection and coding).

Give the procedure for selecting studies for the review and extracting data, including the number of researchers involved and how discrepancies will be resolved. List the data to be extracted.

The selection of the included studies will be made by two independent reviewers accordingly to pre-established inclusion and exclusion criteria. In case of discrepancies, a third field experienced reviewer willbe consulted.

The data extraction will be made by two independent reviewers. The extracted data from the included studiesare the follow: authors, year of publication, sample number, sample characteristics (age, gender), depth of immersion during walking on shallow water, velocity of walking, bio mechanical and physiological variables (mean ± sd) evaluated during walking.

27. Risk of bias (quality) assessment.

State whether and how risk of bias will be assessed (including the number of researchers involved and howdiscrepancies will be resolved), how the quality of individual studies will be assessed, and whether and howthis will influence the planned synthesis.

The risk of bias assessment of the included studies will be made based on the checklist of Down and Black(The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J. Epidemiol. Community Health. 1998 ; 52 :

377-84).

28. Strategy for data synthesis.

Give the planned general approach to synthesis, e.g. whether aggregate or individual participant data will be used and whether a quantitative or narrative (descriptive) synthesis is planned. It is acceptable to state that a

quantitative synthesis will be used if the included studies are sufficiently homogenous.

Standardized mean differences with 95% confidence intervals will be calculated comparing the outcomes between the water and dry land conditions. A meta-analysis will be executed if sufficient data will be available and methodological homogeneity beteween the studies will be present.

Forest plot distribution will be developed to present findings for similar outcomes domains, and when there was numerical data available for at least two studies reporting the same outcome.

Authors will be contacted through emails for unreported data. Results will be presented as means standardized differences and calculations will be performed using random effects models. Statistical heterogeneity of treatment effects among studies will be evaluated by Cochran's Q test and I^2 inconsistency test, and values above 50% indicate high heterogeneity. Values of alfa = 0.05 will be considered statistically significant and all analysis will be performed using Comprehensive Meta-Analysis Software version 3.3.070.

29. Analysis of subgroups or subsets.

Give details of any plans for the separate presentation, exploration or analysis of different types of participants (e.g. by age, disease status, ethnicity, socioeconomic status, presence or absence or co-morbidities); different types of intervention (e.g. drug dose, presence or absence of particular components ofintervention); different settings (e.g. country, acute or primary care sector, professional or family care); or different types of study (e.g. randomised or non-randomised).

Not planned.

30. Type and method of review.

Select the type of review and the review method from the lists below. Select the health area(s) of interest foryour review.

Type of review

Meta-analysis

Yes

Systematic review

Yes

Health area of the review

Musculoskeletal

Yes

31. Language.

Select each language individually to add it to the list below, use the bin icon to remove any added in error.English

There is not an English language summary

32. Country.

Select the country in which the review is being carried out from the drop down list. For multi-nationalcollaborations select all the countries involved.

Brazil

33. Other registration details.

Give the name of any organisation where the systematic review title or protocol is registered (such as with The Campbell Collaboration, or The Joanna Briggs Institute) together with any unique identification numberassigned. (N.B. Registration details for Cochrane protocols will be automatically entered). If extracted data will be stored and made available through a repository such as the Systematic Review Data Repository (SRDR), details and a link should be included here. If none, leave blank.

34. Reference and/or URL for published protocol.

Give the citation and link for the published protocol, if there is oneGive the link to the published protocol.

Alternatively, upload your published protocol to CRD in pdf format. Please note that by doing so you areconsenting to the file being made publicly accessible.

No I do not make this file publicly available until the review is complete

Please note that the information required in the PROSPERO registration form must be completed in full evenif access to a protocol is given.

35. Dissemination plans.

Give brief details of plans for communicating essential messages from the review to the appropriate audiences.

Do you intend to publish the review on completion?

Yes

36. Keywords.

Give words or phrases that best describe the review. Separate keywords with a semicolon or new line. Keywords help PROSPERO users find your review (keywords do not appear in the public record but are included in searches). Be as specific and precise as possible. Avoid acronyms and abbreviations unless these are in wide use.

Gait

Walking

Water

Biomechanics

37.Details of any existing review of the same topic by the same authors.

Give details of earlier versions of the systematic review if an update of an existing review is being registered,including full bibliographic reference if possible.

38.* Current review status.

Review status should be updated when the review is completed and when it is published. For newregistrations the review must be Ongoing.

Please provide anticipated publication dateReview_Ongoing

39. Any additional information.

Provide any other information the review team feel is relevant to the registration of the review.

40. Details of final report/publication(s).

This field should be left empty until details of the completed review are available.Give the link to the published review.

9.2 Annex 2: Study 2 registry at Open Society Foundations

Title

“Wet inverted pendulum”: A physiomechanical model of shallow water walking at different depths and speeds

Research question

There are differences in metabolic, kinetic, and kinematic parameters during shallow water walking by healthy adults at different depths and speeds?

Aims

1. To compare the cost of transport, heart rate, rating of perceived effort, drag force resistance, spatiotemporal, and lower limb angular parameters during walking in shallow water at xiphoid, umbilical, hip, and knee depths at the speeds of 0.2, 0.4, 0.6, 0.8 m/s by healthy adults.
2. To propose a physiomechanical model called wet inverted pendulum, estimating the buoyancy and drag forces

Hypothesis

1. The cost of transport of shallow water walking will have a minimal value at intermediary speeds.

2. The cost of transport behavior would be related to the interplay between buoyancy and drag forces

10.Appendix

10.1 Appendix 1: Study 1 search terms

(walk[tw] OR walking [Mesh] OR gait [Mesh]) AND (“water-based activities” [tw] OR “activities, water-based” [tw] OR “water aerobics” [tw] OR “aerobics, water” [tw] OR “water aerobic exercise” [tw] OR “aerobic exercise, water” [tw] OR “water aerobic exercises” [tw] OR "aerobic exercises, water" [tw] OR “aquatics” [tw] OR “water walking” [tw] OR “walking, water” [tw] OR “shallow water walking” [tw] OR “walking, shallow water” [tw] OR “aquatic environment” [tw] OR “environment, aquatic” [tw] OR “underwater treadmill” [tw] OR “water treadmill” [tw] OR “aquatic treadmill” [tw] OR aquatic [tw] OR water [Mesh] or immersion [Mesh])