UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
ESCOLA DE EDUCAÇÃO FÍSICA, FISIOTERAPIA E DANÇA
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DO MOVIMENTO HUMANO

“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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Dissertação apresentada ao Programa de Pós-Graduação Ciências do Movimento Humano da Escola de Educação Física, Fisioterapia e Dança da Universidade Federal do Rio Grande do Sul como requisito parcial para obtenção do título de Mestre em Ciências do Movimento Humano.

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Coorientadora: Profa. Dra. Flávia Gomes Martinez

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CIP - Catalogação na Publicação

Ivaniski-Mello, André
"WATER IMMERSED INVERTED PENDULUM": A PHYSIOMECHANICAL MODEL OF SHALLOW WATER WALKING AT DIFFERENT DEPTHS AND SPEEDS / André Ivaniski-Mello. -- 2020.
140 f.
Orientador: Leonardo Alexandre Peyré-Tartaruga.

Coorientadora: Flávia Gomes Martinez.

Dissertação (Mestrado) -- Universidade Federal do Rio Grande do Sul, Escola de Educação Física, Programa de Pós-Graduação em Ciências do Movimento Humano, Porto Alegre, BR-RS, 2020.

1. Locomoção. 2. Caminhada em água rasa. 3. Fisiomecânica. 4. Imersão em água. 5. Otimização. I. Peyré-Tartaruga, Leonardo Alexandre, orient. II. Gomes Martinez, Flávia, coorient. III. Título.

Elaborada pelo Sistema de Geração Automática de Ficha Catalográfica da UFRGS com os dados fornecidos pelo(a) autor(a).

AGRADECIMENTOS

Eu gostaria de agradecer primeiramente a todo povo brasileiro que por meio de seus impostos possibilita a realização de um ensino público gratuito de qualidade. E ressaltar a importância de todas as pessoas que fazem o dia-a-dia desse ensino e pesquisa.

Agradeço infinitamente meus pais e meu irmão. A educação e o exemplo que me propiciaram são a base de tudo o que sou. Não tenho palavras e conceitos para descrever a importância de vocês. Espero que possa viver à altura de tudo o que me ensinaram e proporcionaram.

Agradeço também a orientação e os ensinamentos de meus orientadores Dr. Leonardo Alexandre Peyré-Tartaruga e Dra. Flávia Gomes Martinez. A sua paciência e dedicação em ensinar e incentivar o desenvolvimento pessoal e acadêmico de seus alunos são inspiradores. Verdadeiros exemplos para mim tanto no âmbito profissional, quanto pessoal.

Agradeço a todos os integrantes da banca de avaliação Profa. Dra. Cristine Lima Alberton, Prof. Dr. Flávio de Souza Castro, Prof. Dr. Luca Ardigò e Prof. Dr. Marcelo Coertjens pelo gentil aceite e importantes contribuições com o trabalho.

Agradeço a todo o grupo de pesquisa Locomotion e GPCOMFA. O aprendizado, convivência e suporte de vocês foram essenciais por toda essa etapa. Nomeio alguns com receio de esquecer nomes igualmente importantes: Leonardo de Los Santos Bloedow, Marcela Zimmermann Casal, Edson Soares da Silva, Antônio Henrique Leal do Nascimento, Valéria Feijó Martins, Diana Maria Cubillo Arcila, Lucas de Liz Alves, Misael da Silva Camacho, Jennifer Oliveira, Andressa Fiori Bortoli. Agradeço à Daniela Luft pela parceria e confiança em aceitar ser coorientada por mim.

Agradeço a todos os sujeitos voluntários das coletas de dados que permitiram a execução deste trabalho. Agradeço à toda equipe de trabalho do Centro Natatório da Escola de Educação Física, Fisioterapia e Dança da UFGRS, incansáveis em propiciar as melhores condições possíveis para a realização das coletas de dados.

Agradeço à Fernanda Scalco Acco pelo apoio, incentivo e parceria. Sou muito grato por toda a motivação e partilha, e pela possibilidade de convivência e crescimento.

Agradeço à Luiza Rampi Pivotto pelo compartilhamento, escuta e atenção. Sempre vou recordar das conversas que muito me ajudaram a amadurecer ideias e sentimentos ao longo desse período.

Por fim, agradeço a todos os professores que tive ao longo da minha vida acadêmica. Com certeza cada um contribuiu fundamentalmente para minha formação e educação.

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.

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LIST OF ABBREVIATIONS

A: area of body surface
Ap: projected frontal area
B: buoyancy force
C: cost of transport
Cd: drag coefficient
D: body diameter.
DLW: dry land walking
DrF: drag force
Ekf: kinetic forward energy
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
GRF: ground reaction forces
h: height
L: body length characteristic
m: rigid body with mass
m_w**:** mass of water displaced
P: pressure
Pg: potential gravitational energy
Re: Reynolds number
SSWS: comfortable self-selected speed of walking
SWW: shallow water walking
v: velocity
VO2: energy expenditure
V-GRF: vertical ground reaction force
y: vertical axis definition
η**:** fluid viscosity

$\boldsymbol{\rho}$**:** specific mass

$\boldsymbol{\rho_f}$: fluid specific mass

$\boldsymbol{\rho_w}$**:** 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).

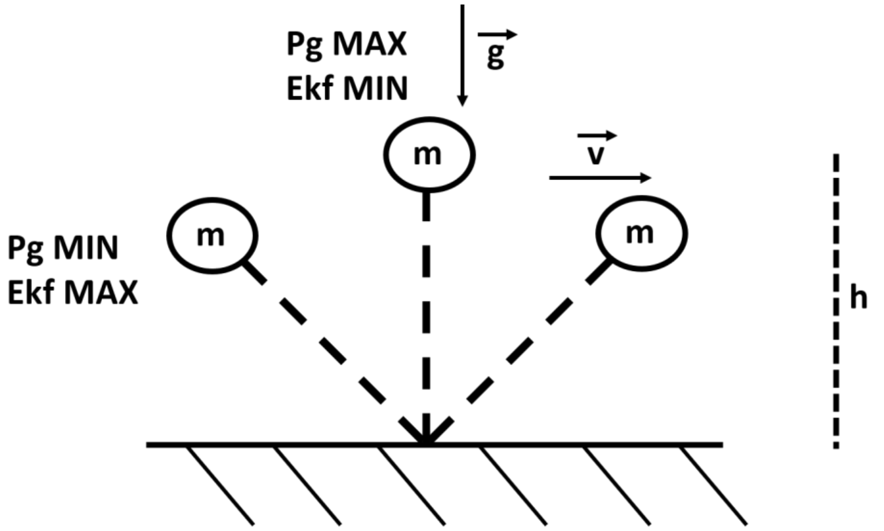

Figure 1 - Inverted pendulum during dry land walking. Ekf: kinetic forward energy; g: gravitational acceleration; h: height; m: rigid body with mass; Pg: potential gravitational energy; v: velocity.

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).

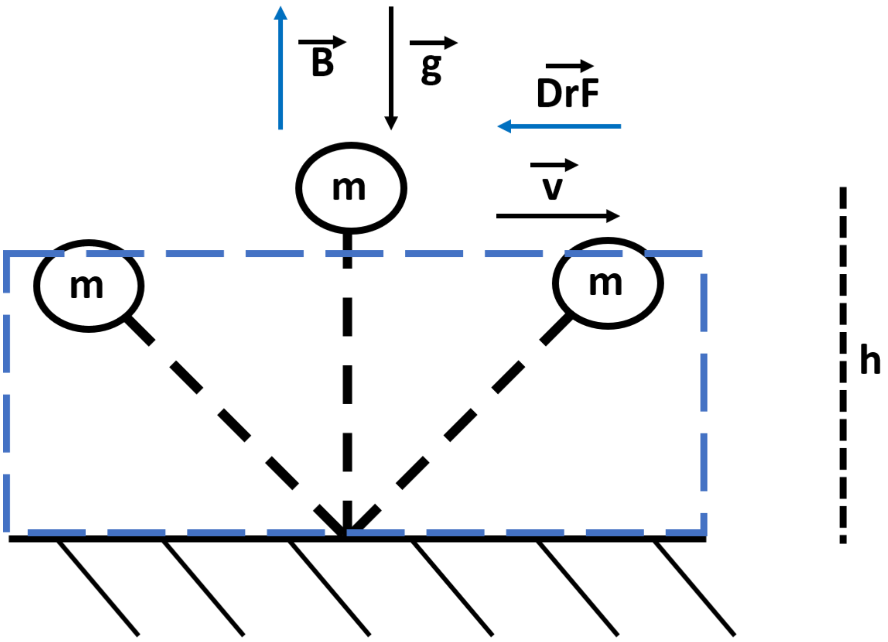

Figure 2 - The inverted pendulum during shallow water walking ("water immersed inverted pendulum"). B: buoyancy force; DrF: drag force; g: gravitational acceleration; h: height; m: rigid body with mass; v: velocity.

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).

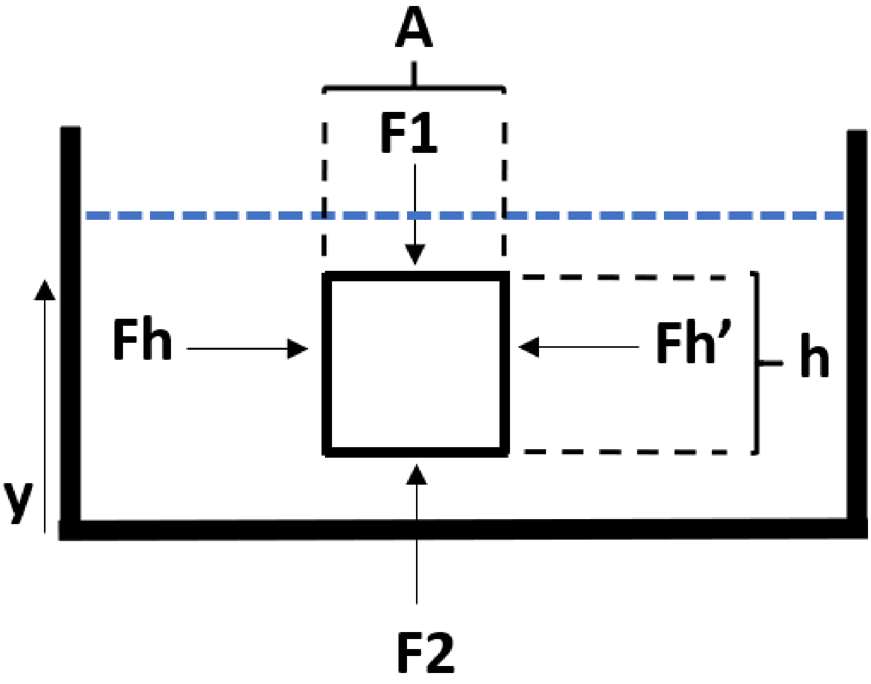

Figure 3 - Hydrostatic pressure of a fluid on a cubical immersed body. A: area of body surface; F1: total force in superior body surface; F2:

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).

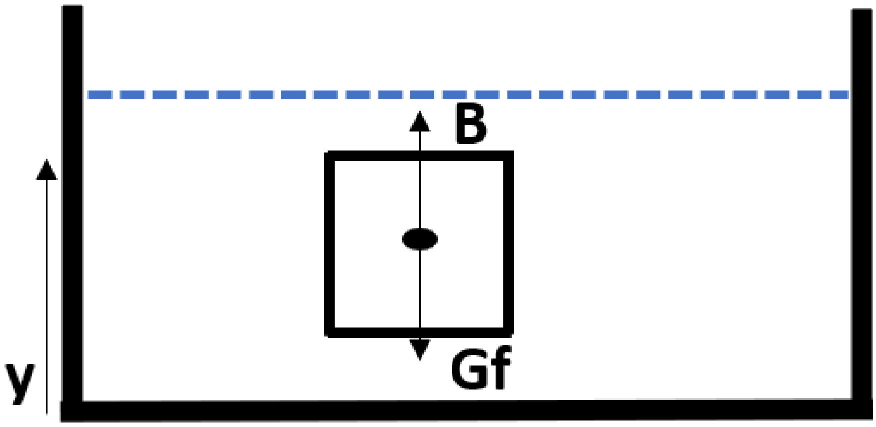

Figure 4 - Buoyancy and gravitational forces applied on an immersed body. B: buoyancy force; Gf: gravitational force; y: vertical axis definition.

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.

<u>Equation 1 development</u>

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 deacclerate the body (FOX; MCDONALD; MITCHELL, 2018)

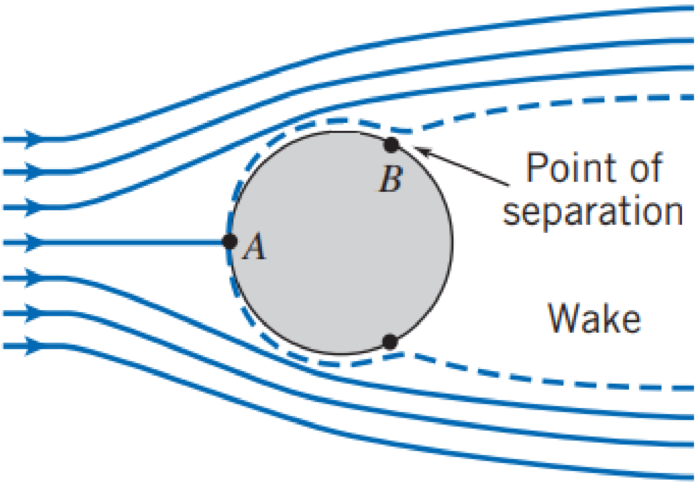

Figure 5 - Fluid flow on an immersed body at higher Reynold number creating a low-pressure wake region. A: high pressure point. B: point of separation of boundary layer. Figure extracted and adapted from Fox, McDonald, Mitchell (2018).

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).

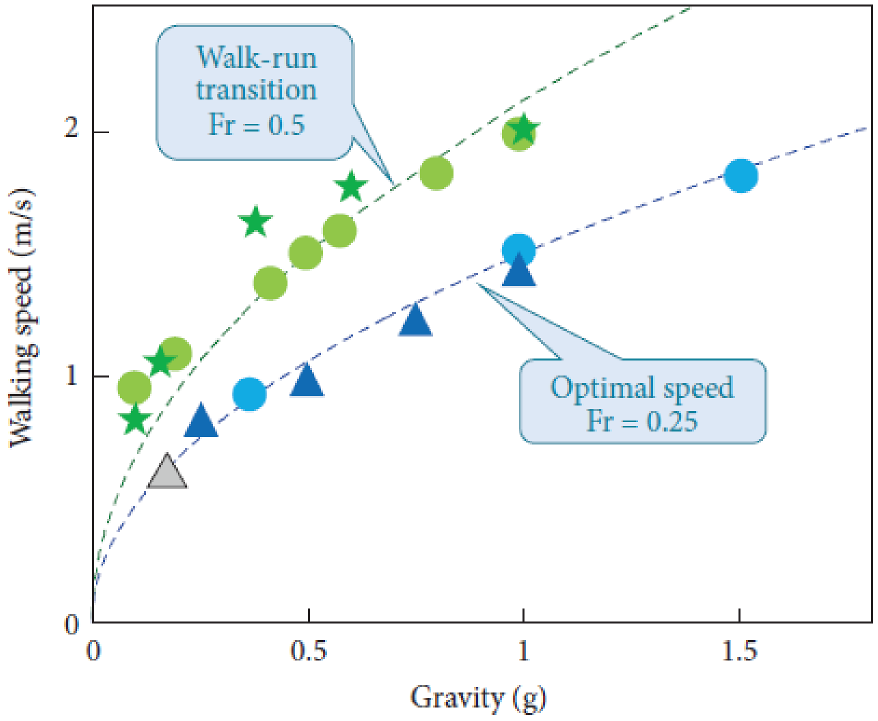

Figure 6 - Walking-running transition and optimal walking speeds at different gravity conditions. Fr: Froude number. Each type symbol represents one study different. Blue circle: Cavagna, Willems and Heglund (1998, 2000); blue triangle: Griffin, Tolani and Kram (1999); green circle: Kram, Domingo and 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

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

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 7).

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.

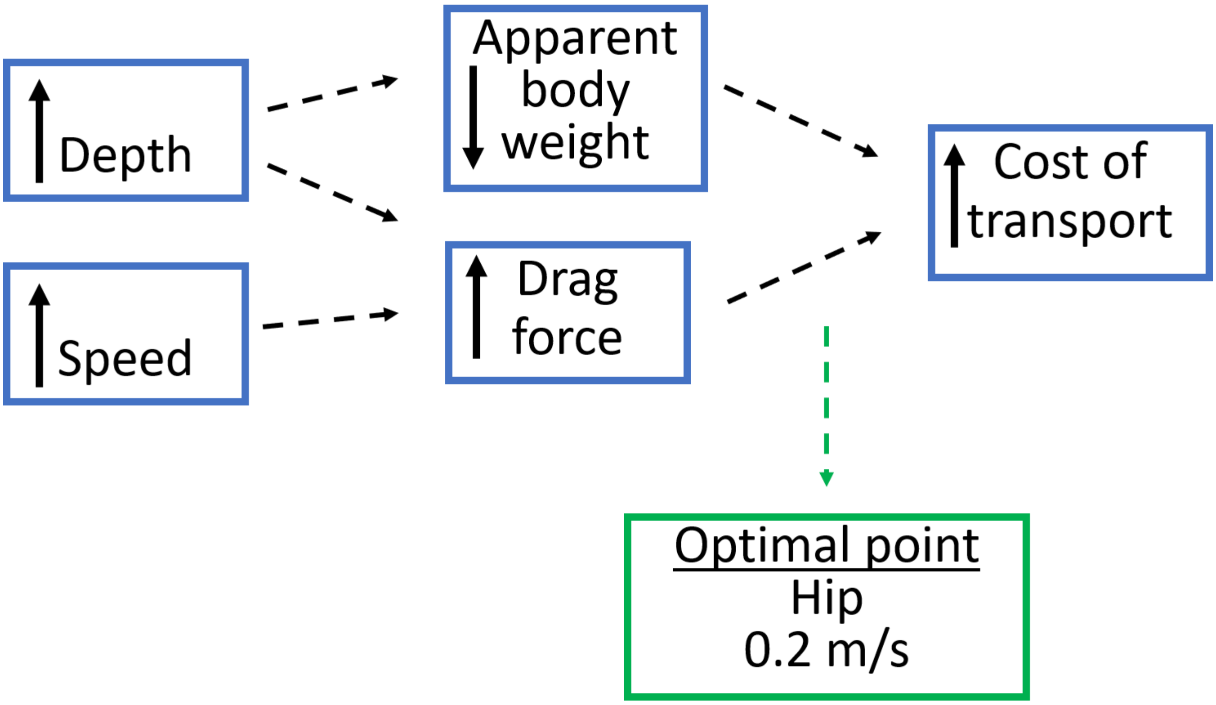

Figure 7 - Conceptual model for physiomechanics of shallow water walking.

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9. Annex

9.1. Annex 1 - Study 1 registry in PROSPERO

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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])