Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Gait & Posture 24 (2006) 412–417

GAIT & POSTURE

www.elsevier.com/locate/gaitpost

Dynamometric analysis of the maximum force applied in aquatic human gait at 1.3 m of immersion

Helio Roesler *, Alessandro Haupenthal, Gustavo R. Schütz, Patrícia V. de Souza

Aquatic Biomechanics Laboratory, Center of Physical Education, Physiotherapy and Sports of Santa Catarina State University, 358, Paschoal Simone Street, ZC 88080-350 Coqueiros, Florianopolis, Brazil

Received 30 August 2004; received in revised form 5 May 2005; accepted 12 September 2005

Abstract

Background: This work had the objective to analyze the values of the vertical and anteroposterior components of the ground reaction force (GRF) during the aquatic gait and the influence of the speed and the upper limb position on the GRF components values.
Methods: Sixty subjects, with average height between 1.6 and 1.85 m and average age of 23 years, were divided in three groups according to the immersion level. The citizens walked over a walking platform, which had two force plates attached. The platform was located at a depth of 1.3 m. The subjects walked over the platform in four different situations, with speed and upper limb position variations. For data analysis, descriptive and inferential statistics were used.
Findings: For the vertical component, the force values varied between 20% and 40% of the subjects' body weight according to the different data collection situations. For the anteroposterior component, the force values reached between 8% and 20% of the subjects' body weight corporal, also according with the data collection situation.
Interpretation (discussion): It was noted that for a given immersion level, the forces can vary according to the request that is imposed to the aquatic gait. It was concluded that either the speed as well as the position of the upper limb influence the values of the GRF components. An increase in the gait speed causes increase of the anteroposterior component (Fx), while an increase in the corporal mass out of the water causes increase mainly of the vertical component (Fy). Knowing the value of these alterations is important for the professional who prescribes activities in aquatic environment.

Keywords: Aquatic gait; Ground reaction force; Underwater force platforms

1. Introduction

The over ground gait has been extensively studied over the years [1–3]. However, the studies considering underwater gait are less numerous [4]. Despite the frequent use of the aquatic environment in training and rehabilitation, there are few works directed to this subject.

In 1987, Harrison and Bulstrode [5] studied the values of load reduction experienced by the human locomotory system in aquatic environment, through the measuring of the hydrostatic weight of subjects in several levels of immersion. The reduction of the hydrostatic weight was used as basis for several studies concerning aquatic activities, although it was believed that the values would vary when the subjects moved themselves.

Harrison et al. [6] also studied the dynamic variables of underwater gait in 1992. This study was measured for the first time the vertical ground reaction force in nine subjects (six women and three men), with height varying between 1.65 and 1.82 m. The authors compared the immersion levels of 1.1 and 1.3 m with the subjects walking outside the water in two speeds (slow and fast).

Nakasawa et al. [7] and Yano et al. [8] carried out a study about the vertical component of the ground reaction force (GRF) during over ground and underwater gait using a water resistant force plate developed to this study.

* Corresponding author. Tel.: +55 48 8405 5797; fax: +55 3223 9292.
E-mail addresses: d2hr@udesc.br (H. Roesler), pativs@hotmail.com (P.V. de Souza).

0966-6362/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2005.09.014

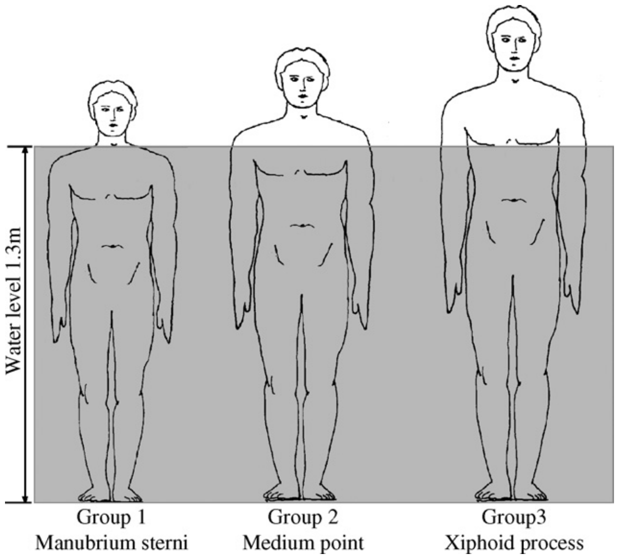


Fig. 1. Immersion level view of the three groups.

Yamamoto et al. [9] analyzed the vertical force and angular variation of the hip, knee and ankle joints at 1.2 m depth. Three subjects participated in the study, and five steps over a walking platform were recorder for each subject. The speed (normal walking speed) was self-selected by each subject. The subjects were then requested to increase and decrease the speed, based on the self-selected normal walking speed.

Brito et al. [10] analyzed the vertical component of the ground reaction force of the gait in individuals immersed at hip and knee joints levels, through the use of underwater force platforms [11].

The present study analyzed two GRF vertical and anteroposterior components during underwater gait, as well as the influence of speed and upper limb position on the GRF values.

The values of the GRF components underwater can provide valuable information regarding the resultant force acting on the individual performing the task. This is crucial for training prescription and rehabilitation work in the aquatic environment.

2. Methods

After approval of the Research Ethics Committee of Santa Catarina State University, Center of Physical Education, Physiotherapy and Sports, the subjects were asked to participate in the study. The sample was composed of 60 subjects (28 female and 32 male), with height varying between 1.6 and 1.85 m and no gait disorders were selected for the study. The average age of the participants was 23 ($\pm$5) years.

The water depth was set at 1.30 m. Due to the fact that the height of the subjects could interfere in the GRF values, the sample was divided in three groups. The division was performed to facilitate the exercise prescription in the aquatic environment, through the selection of a standard anatomical point that could be easily identified for all the subjects. The groups were divided in three levels of immersion: (1) manubrium sterni, (2) medial point between the manubrium sterni and xiphoid process sterni distance and (3) xiphoid process sterni (Fig. 1).

The anthropometric characteristics of the 60 subjects are described in Table 1.

The group 1 was composed of 19 women and 1 man, while group 2 was composed of 10 women and 14 men. Finally, group 3 was composed of 1 women and 15 men. The variation coefficient of the immersion level was 2.0%, 1.9% and 2.0%, respectively, for the groups 1, 2 and 3; which indicates good homogeneity.

In order to collect the force data, a 6.15 m long walkway platform containing two underwater force plates was placed at the bottom of a thermal swimming pool (30 $\pm$ 1 °C). The underwater force plates (Roesler, 1997; dimensions 500 mm $\times$ 500 mm $\times$ 200 mm) have a sensitivity of 2 N, error lower than 1% and 60 Hz of native frequency. The vertical (Fy) and anterior–posterior (Fx) components of the GRF were acquired, with a sampling frequency of 600 Hz. The system for the acquisition of dynamometric data also was completed by a CIO-EXP-BRIDGE board of 16 channels and by the converter TO/D CIO-DAS-16Jr, both with capacity for 16 channels and from the company Computer Boards. For signal analysis and editing, the system SAD 32, version 3.0 [12] was used.

Data collection procedures began with the measuring of the anthropometric data as follows: (a) body weight of the subjects using an electronic scale (Plenna, model MEA-08128, scale of 0.1 kg); (b) height of the subjects; (c) the distance from the points xiphoid process and manubrium sterni to the ground, with the use of a metric tape; (d) subjects' coetaneous folds using a scientific caliper (CESCORF, scale 0.1 mm).

The corporal density for the male subjects was calculated through a regression equation using the sum of the triciptal,

Table 1
Sample characteristics divided in groups

	Xiphoid process distance upon ground (m)	Medium point distance upon ground (m)	Mubrium sternis distance upon ground (m)	Stature (m)	Weight (kg)	Density (g/ml)	Number of subjects (*n*)
Group 1	1.16 $\pm$ 0.02	1.25 $\pm$ 0.02	1.34 $\pm$ 0.03	1.65 $\pm$ 0.04	57.6 $\pm$ 5.5	1.0466 $\pm$ 0.008	20
Group 2	1.22 $\pm$ 0.02	1.31 $\pm$ 0.03	1.40 $\pm$ 0.04	1.72 $\pm$ 0.04	65.6 $\pm$ 9.6	1.0648 $\pm$ 0.019	24
Group 3	1.30 $\pm$ 0.03	1.39 $\pm$ 0.03	1.47 $\pm$ 0.04	1.80 $\pm$ 0.04	75.5 $\pm$ 10.4	1.0719 $\pm$ 0.011	16

Table 2
Aquatic gait situations

Abbreviation	Gait situation
ISG	Slow gait with the upper limb inside the water beside the body—named inside slow gait
OSG	Slow gait with the upper limb outside the water—outside slow gait
IQG	Gait with the upper limb inside the water, the fastest speed the subject obtained—inside quick gait
OQG	Gait outside the water, the fastest speed the subject obtained—outside quick gait

pectoral and subescapular skinfolds [13]. In women, the regression equation used the sum of triciptal, abdominal and supra iliac [14].

After the anthropometrical measurements, the subjects were asked to enter in the pool. Each subject had an adaptation period, in order to get used to the equipment and the data collection conditions. For the data collection, the subjects were instructed to walk over the walkway in four distinct situations, exposed in Table 2.

In order to control the walking speed (ISG and OSG), a digital metronome (Korg, model MA-20) was used, with a 40 counts/min frequency. Each count of the metronome corresponded to the beginning of the stance phase from the gait. The speed was later verified through kinematics analysis, with the use of a digital camera. The average speed for the condition ISG was 0.41 ($\pm$0.05) m/s and for the condition OQG was 0.43 ($\pm$0.03) m/s. For the fast walking situations, IQG and OQG, the subjects were asked to walk as fast as they could, without the help of the metronome. In addition, the following criteria were observed for the fast walking situations: the subjects should not present either loss of balance or fall off the walkway platform, they should not balance themselves with the help of the upper limbs (beat the hand on the water) and they should not run. The average speed for the IQG situation was 0.55 ($\pm$0.06) m/s and for OQG situation was 0.66 $\pm$ (0.06 m/s).

Each subject performed four passages in the footbridge for each of the four data collection situations, with a total of 16 curves of forces by subject. The total number of force curves was 960 (480 for each component Fy and Fx). After categorizing the subjects, the force curves were analyzed through the following phases: (1) application of the calibration coefficient and filters (filter FFT Butterworth with a low-pass cutoff frequency of 30 Hz and order 3); (2) normalization by the body weight measured outside the water (in order to observe the percentual reduction of the values of force in comparison with the values outside the water); (3) Verification of the maximum force value for each curve (Fy and Fx).

For this study, the maximum force is defined as the maximum value presented by the GRF components, normalized by body weight, occurring at any period of time from the beginning until the end of the curve (Fig. 2). Due to the fact that the force–time curve obtained for the vertical component of the GRF when walking underwater is very irregular, the maximum peak force can occur at any time, not necessarily at the same time of the first or second peaks when walking over ground. Other characteristic that can be observed during underwater walking, is that the negative phase of the curve from the anteroposterior component, commonly seen in over ground walking, does not happen every time during underwater walking. Although it appers in some curves, it does not appear in the group's general media.

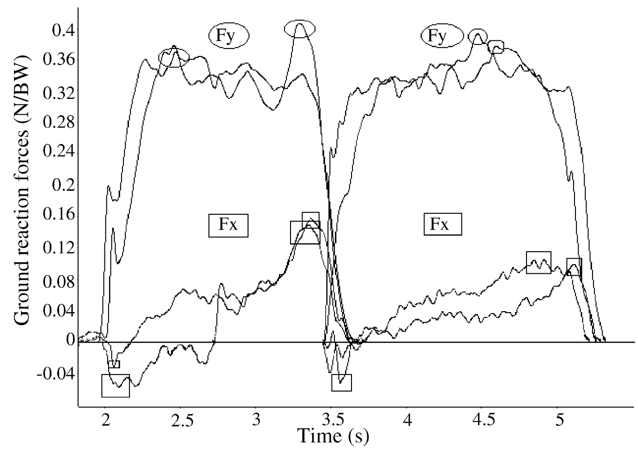


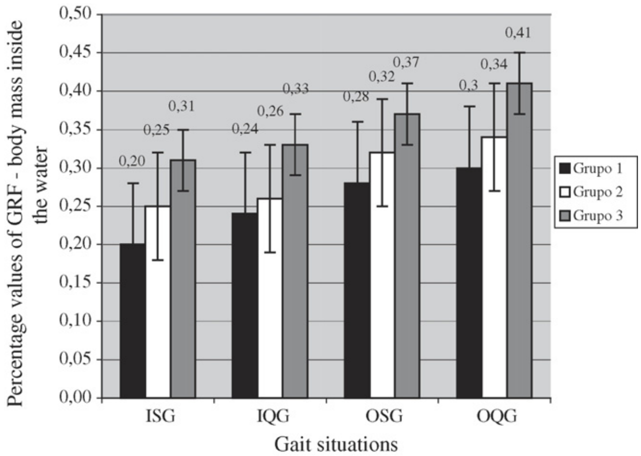
Fig. 2. Ground reaction force curve for two subjects of group 3 with upper limb out of the water and slow speed. The vertical component (Fy) maximum values are circled. The anteroposterior component (Fx) maximum values are squared.

For data analysis, descriptive statistics (media, standard deviation and coefficient of variation) and inferential statics ("t" tests for matched samples, ANOVA and Post Hoc through Tukey HSD) were used. The level of significance was set at $p < 0.01$, both for the ANOVA, as well as for the Post Hoc analysis. The statistical analysis was performed with the use of the software Microsoft Excel and the statistical package SPSS version 10.0 (Tritschler [15]).

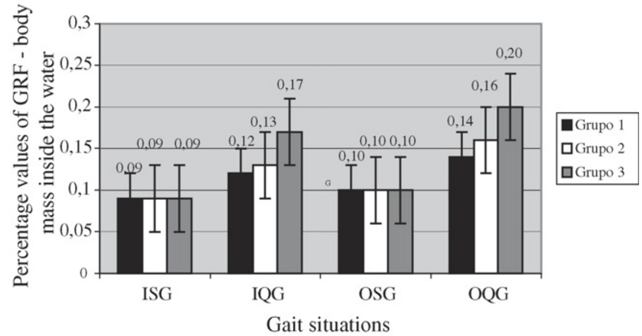
3. Results

Comparing the vertical force values in relation to the speed (slow $\times$ fast), among each group separately (ISG $\times$ IQG and OSG $\times$ OQG), it was noted that the force values increase as the speed increases (Graph 1), but the statistics analysis did not show any significant differences. Comparing the values in relation to the gait situations concerning the upper limb inside $\times$ outside the water, it was found that the values increase significantly as the upper limb moves out of the water, with significant differences ("t" tests for matched samples $p < 0.01$ between ISG $\times$ OSG and IQG $\times$ OQG).

The analysis concerning the water levels differences show that comparing groups 1 $\times$ 2, it was noticed that as the water level decreases (from the point over the manubrium sterni to the medium point between manubrium sterni and



Graph 1. GRF vertical components media and standard deviation values for groups 1–3 in the three different situations.



Graph 2. GRF anteroposterior components media and standard deviation values for groups 1–3.

the xiphoid process), the vertical force increases significantly 4% in average $p < 0.01$). The speed analysis showed significant differences (ANOVA and Post Hoc through Tukey HSD $p < 0.01$). Comparing groups 3×1, the decrease in the water level from manubrium sterni to the xiphoid process caused a significant increase in the vertical forces, 10% in average. Comparing groups 3×2, the decrease in the water level from the medium point to the xiphoid process causes Fy (vertical force) to increase significantly 6% in average, differences confirmed for the fast speeds (ANOVA and Post Hoc through Tukey HSD $p < 0.01$).

For a better understanding of the alteration that occurs during underwater gait, a force × time curve, representing the vertical component of the GRF at 1.3 m of immersion is compared to a GRF curve obtained during over ground walking. It is noticed that a rectification (flattening) of the curve occurs. Thus, the peaks are next to deflection and the load absorption happens in a larger time until the first peak force. The "M" shaped curve, common for the vertical component of the GRF during over ground gait is not characterized inside the water and the curve shape is similar to a trapezium.

Comparing the anteroposterior force values in relation to the speed (slow × fast), among each group separately, it can be seen that the values increase as the speed increases (Graph 2), with significant differences for all the three groups ("*t*" tests for matched samples $p < 0.01$). Comparing the gait situations with the upper limb inside and outside the water, the values do not increase significantly (ANOVA and Post Hoc through Tukey HSD $p < 0.01$).

For the slow gait situations, the anteroposterior force did not vary among the groups 1–3. In the fast gait situations, comparing groups 2 and 1, the forces presented a 2% increase. Comparing the groups 1 and 3, decreasing (lowering) the water level from manubrium sterni to the xiphoid process, the force increases 6%. Comparing groups 3 and 2, the anteroposterior force increases 4%. There was a significant difference for all 3 groups for the fast speed gait situations (ANOVA and Post Hoc through Tukey HSD $p < 0.01$) (Fig. 3).

The comparison between the force × time curves for the anteroposterior component of the GRF at 1.3 m of immersion is represented in Fig. 4. The figure shows that, differently from over ground gait, during underwater gait the negative phase of the curve does not occur, and the force increases gradually until it reaches a peak. The anteroposterior curve for the underwater gait is similar to a rectangle triangle, differently from the over ground gait curve.

To analyze the reduction in the vertical and anteroposterior components of the GRF during underwater gait, the values were compared to the over ground gait values (Graphs 3 and 4). The values used to calculate the force reduction were 1.2 N/BW for the vertical component and 0.2 N/BW for the anteroposterior component. These values are referred in the literature [15,1–3,16,17]. The comparison shows that the maximum values of the vertical force decrease with the reduction of the immersion level, upper limb withdrawal off the water and speed increase. For the anteroposterior component of the GRF, the values decrease specially with the speed increase.

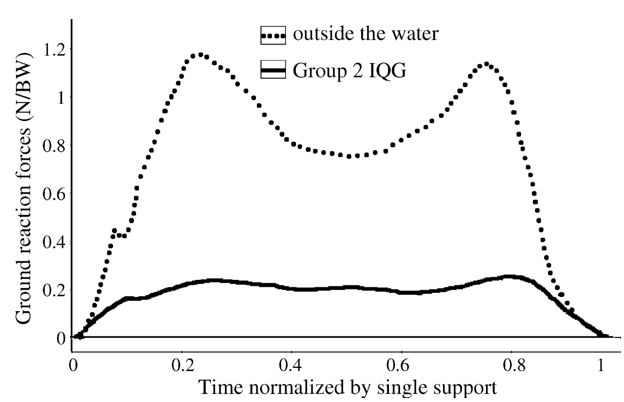


Fig. 3. Comparing the force × time curves for GRF vertical component outside the water (1.2 m/s) and aquatic gait (0.5 m/s).

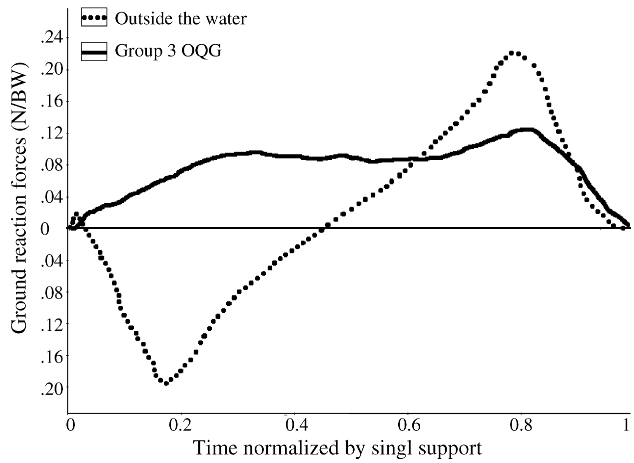
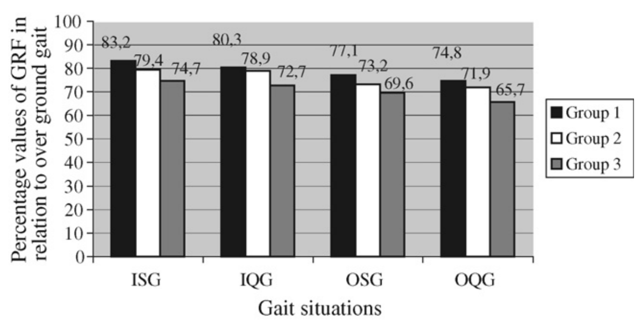


Fig. 4. Comparing the force × time curves for GRF anteroposterior component outside the water (1.2 m/s) and aquatic gait (0.66 m/s). (In order they are referenced in the text and sequenced below.)



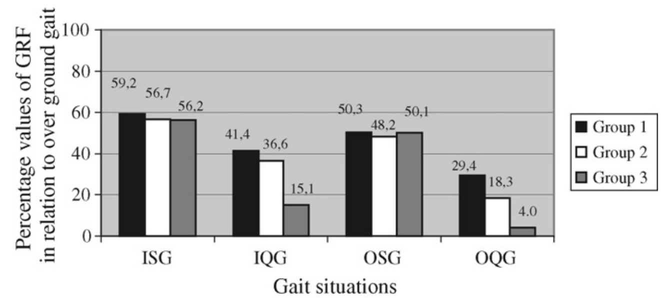
Graph 3. Maximum force reduction of the GRF vertical component for aquatic gait compared to the reference values for land gait.

4. Discussion

Based on the results, alterations in the vertical components of the GRF according to the immersion level can be observed. The water withdrawal of the upper limb caused significant increase in the force values as much as the water level reduction did. To consider this increase of the vertical component of the GRF caused by a slight change in the water level is fundamental to support the prescription of exercises and therapeutic rehabilitation processes used by the professionals who work with aquatic activities [18–20].

The values found in this study for maximum force in the vertical component of the GRF, even for group 3 in the OQG situation, are inferior to the ones previously reported by Harrison and Bulstrode [5]. Similar values to this gait situation are related by Brito et al. [10], at a immersion level corresponding to the body hip joint.

The anteroposterior component presents a negative peak in over ground gait, related to the movement breakdown, and a positive peak, due to acceleration. For the positive peak, it is observed that the maximum force increases significantly with the speed upgrade during underwater gait. For the slow speed situations, the force values reached about half of the values found for over ground gait. Indeed, for the fast speed



Graph 4. Maximum force reduction of the GRF anteroposterior component for aquatic gait compared to the reference values for land gait.

situations, there was not such a significant reduction, specially when considering group 3 OQG, where the values are very close to over ground gait values, despite a slower speed in the water. The alteration of the immersion level does not increase the maximum force in this component.

The negative peak, for most of the subjects, did not occur. This alteration causes the curve shape to look like a triangle. For the subjects that had a negative peak, the peak occured mainly for the slow speed situations. It can be corroborated by the fact that in group 3, where the immersion level was lower, the highest negative peaks occurred.

The reason that the negative peak does not occur for the fast speed situations may be because the subject modifies the gait support phase in the water, in an effort to gain speed. The subject performs only the propulsion phase of the movement, leaning the body forward and touching the platform only when the leg had already passed the body axis. Therefore, if the treatment goal is to train the gait of a subject functionally not so seriously compromised, the underwater gait which approximates the most to over ground gait is at the xiphoid process immersion level, upper limb outside the water and the fastest possible speed sustained by the subject.

Observing Graph 4, it shows that the maximum force reduction decreases from groups 1 to 3, and from ISG to OQG situations. The most conservative situation (when it comes to safety) is at manubrium sterni immersion level, upper limb inside the water and slow speed. Opposite to this situation, there is the immersion level at xiphoid process, upper limb outside the water and fast speed. That means the load can be gradually increased during the underwater gait of a subject passing from situation 1 ISG until 3 OQG.

5. Conclusions

It is concluded that even without changing the immersion level the GRF components can be altered, through the upper limb position and gait speed. An alteration in the curve patterns (shape) can also be confirmed: the vertical component is similar to a trapezium and the anteroposterior is similar to a triangle.

This work suggests that an increase in the gait speed results in an increase in the anteroposterior component, while an increase in the body mass outside the water produces an increase mainly in the vertical component. Knowing these values and their relations in each situation is crucial to the prescription of activities in aquatic environment.

References

[1] Perry J. Gait analysis: normal and pathological function New York: MacGraw-Hill; 1992.
[2] Rose JE, Gamble JG. Marcha humana., 2a ed., São Paulo: Premier; 1998.
[3] Winter DA. The biomechanics and motor control of human gait: normal, elderly and pathological, 2nd ed., Canada: Waterloo Cover; 1991. p. 1.
[4] Becker BE, Cole AJ. Terapia Aquática Moderna São Paulo: Manole; 2000.
[5] Harrison R, Bulstrode S. Percentage weight bearing during partial immersion in the hydrotherapy pool. Physiother Pract 1987;3:60–3.
[6] Harrison R, et al. Loading of the lower limb when walking partially immersed. Physiotherapy 1992;78(3):164–6.
[7] Nakazawa K, Yano H, Miyashita M. Ground reaction forces during walking in water. Medicine and science in aquatic sports, Vol. 39 Karger; 1994. p. 28–34.
[8] Yano H, Nakazawa K, Yamamoto S. Activation patterns of human ankle muscles during walking in water. Book of abstracts Xvth Congress Isb; 1995. p. 1018–19.
[9] Yamamoto S, Yano H, Nakazawa K. Lower limb kinematics during walking in water. Book of abstracts Xvth Congress Isb; 1995. p. 1012–13.
[10] Brito RN, Roesler H, Haupenthal A, Souza PV. Análise Comparativa da marcha humana em solo à subaquática em dois níveis de imersão: joelho e quadril. Revista Brasileira de Fisioterapia 2004;8:7–12.
[11] Roesler H. Desenvolvimento de plataforma subaquática para medições de forças e momentos nos três eixos coordenados para utilização em Biomecânica. Tese de Doutorado-Programa de pós-graduação em Engenharia Mecânica Porto Alegre: Universidade Federal do Rio Grande do Sul; 1997.
[12] Sad 2 Versão (3.0). Sistema E Aquisição De Dados–Manual De Operação. Porto Alegre: Caderno Técnico da Engenharia Mecânica CT 07–DEMEC; 1997.
[13] Pollock ML, Jackson AL. Generalized equations for predicting body density of men. Br J Nutr 1978;40:497–504.
[14] Pollock ML, Jackson AL, Ward A. Generalized equations for predicting body density of women. Med Sci Sports Exerc 1980;12:175–82.
[15] Tritschler K. Medida e Avaliação Em Educação Física E Esportes. São Paulo: Manole; 2003.
[16] Nigg BM, Herzog W. Biomechanics of the musculo-skeletal system. John Wiley & Sons; 1994.
[17] Hennig G. Gait analysis and the biomechanics of human locomotion. Florianópolis: Anais VIII Congresso Brasileiro de Biomecânica; 1999. p. 19–26.
[18] Skinner AT, Thomson AM. Duffield: Exercícios Na Água, 3rd ed., São Paulo: Manole; 1985.
[19] Bates A, Hanson N. Exercícios Aquáticos Terapêuticos São Paulo: Manole; 1998.
[20] Schütz GR, Haupenthal A, Roesler H. Estudio dinamometrico de la marcha humana en el medio acuático. Revista Digital Efdeportes, Año 10, n. 81, Febrero de; 2005.