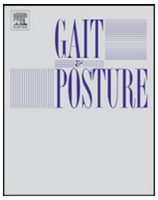
Gait & Posture 33 (2011) 635–639

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost



Day-to-day consistency of lower extremity kinematics during stair ambulation in 24–45 years old athletes

Johanna Husa-Russell [a,b,*], Thomas Ukelo [a], Renate List [a], Silvio Lorenzetti [a], Peter Wolf [c]

[a] ETH Zurich, Institute for Biomechanics, Wolfgang-Pauli-Str. 10, CH-8093 Zurich, Switzerland
[b] University of Eastern Finland, Institute of Biomedicine, Kuopio Campus, P.O. Box 1627, FI-70211 Kuopio, Finland
[c] ETH Zurich, Institute of Robotics and Intelligent Systems, Sensory-Motor Systems Lab, Tannenstrasse 1, CH-8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 14 June 2010
Received in revised form 4 February 2011
Accepted 14 February 2011

Keywords:
Instrumented gait analysis
Stairs
Range of motion
Reliability

ABSTRACT

Before making interpretations on the effects of interventions or on the features of pathological gait patterns during stair ambulation, the day-to-day consistency of the investigated variables must be established. In this article, the day-to-day consistency was determined for kinematic variables during barefoot stair ambulation. Ten healthy athletes performed two gait analysis sessions, at least one week apart, utilizing a marker set of 47 skin markers, and a functional joint center/axes determination. Being found on limits of agreement and mean differences between the repeated stair ambulation sessions, totally 43 ranges of motions were examined at the hip, knee, ankle, and midfoot joints. The day-to-day consistency was generally in the magnitude of three degrees, irrespective of test condition, investigated joint, or regarded cardinal body plane. The reported values of the day-to-day consistency provide guidelines to distinguish between pathological and healthy gait patterns, and thresholds to determine minimal effects of interventions during stair ambulation.

1. Introduction

Instrumented, three-dimensional gait analysis is frequently used for research on human locomotion as well as for investigation of gait pathologies in clinical studies. In order to appropriately interpret differences between healthy and pathological gait, or between a gait pattern before and after a therapeutic intervention, reliability of the data has to be confirmed [1].

Accordingly, research has been carried out into the day-to-day consistency of biomechanical variables during walking [2–4] and running [4–6]. However, day-to-day consistency in stair ambulation has not been reported although this condition is clinically quite relevant: ascending and descending stairs often induces pain for e.g., individuals with knee or hip osteoarthritis, and patients with patellofemoral pain [7–9].

Many reliability studies are based on an intraclass correlation coefficient or the coefficient of multiple correlations. Distinct categories of reliability based on correlation coefficients have been defined, e.g., coefficients ranging from 0.7 to 0.8 indicate a 'moderate' and coefficients above 0.9 a 'good' reliability [10]. However, these measures of the so-called 'relative consistency' are highly influenced by the magnitude of the ranges of motion: larger ranges of motion will result in higher reliability coefficients. Additionally, a high correlation may still mean an unacceptable measurement error when statistical criteria, which are not based on any well-defined analytical goal, are employed [11].

On the contrary, measures of 'absolute' consistency are more appropriate since they are in the unit of the variable of interest, and estimate the limit between the consistency of the measurement and detectable changes of the gait pattern. Such 'absolute' measures can be obtained by calculating differences between repeated measurements [12].

The scope of this study is to determine the day-to-day consistency of kinematic variables from the midfoot, ankle, knee, and hip joints along all three principal planes (sagittal, frontal and transversal) captured during barefoot stair ambulation. Limits differentiating day-to-day variability from an altered stair ambulation pattern are calculated.

2. Materials and methods

Ten healthy athletes (three females, seven males) with no history of operations or injuries in the lower extremities participated in the study. They were 24–45 years old, their body mass ranged from 54 to 85 kg, and their height was between 1.66 and 1.91 m. The athletes gave their written informed consent prior to data collection. The study was approved by the research ethics committee of the Swiss Federal Institute of Technology, Zurich.

Each athlete performed two test sessions, which were at least one week apart (mean time between session 1 and session 2: 15 weeks, range 1–54 weeks). Both sessions began with a relaxed reference standing. Subsequently, basic motion tasks

---

[*] Corresponding author at: ETH Zurich, Department of Mechanical and Process Engineering, Institute for Biomechanics, HCI E 451, Wolfgang-Pauli-Str. 10, CH-8093 Zurich, Switzerland. Tel.: +41 44 63 36 297; fax: +41 44 6331124.
E-mail address: husaj@ethz.ch (J. Husa-Russell).

0966-6362/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2011.02.009

were performed to determine joint centers/axes for the ankle, knee, and hip joints using functional methods [4,13,14]. In both stair ascending and descending a minimum of ten trials (up to 22, a half of trials beginning with the right leg, and the other half with the left leg) were recorded. A staircase of seven steps was used (Fig. 1) [15]. Its inclination of 30.5°, its run of 29 cm, and its rise of 17 cm were in the range of standard staircases used in other studies [16–18]. Kinematic data was opto-electronically monitored by a motion capture system (twelve MX 40 cameras, Vicon Motion Systems, Oxford, UK). The measuring volume covered a space of 3 m × 5 m × 2 m (width, length, height), and data was recorded at a sampling rate of 100 Hz.

The marker set consisted of 47 markers on the lower extremities. The placement of the markers was performed by the same assistants, who were used to gait analysis. The definition of the applied joint coordinate systems and the corresponding data processing has recently been published [4]. The determination of the segmental position and orientation was based on a least-squares fit of redundant marker point clouds [19]. The description of the intersegmental joint rotations was based on a helical axis approach and a decomposition of the attitude vectors on orthogonal anatomically defined joint coordinate systems [20].

Based on the functionally estimated joint coordinate systems and anatomical landmarks, a segment fixed coordinate system was defined to represent the segment vertical, mediolateral and anteroposterior orientation. Each segment was then rotated such that its segment fixed coordinate system was aligned to the laboratory coordinate system, resulting in a virtually aligned reference. This virtual alignment provided a standardized neutral position of the segments of a subject, which was still dependent on anatomical landmarks and joint center definition, but independent of the standing trial.

The reliability analysis was based on 43 ranges of motion (ROM), which were defined and calculated as differences between the minimum and maximum angular joint displacement during the entire stance phase, or at the beginning or at the end of it (see Fig. 2). These ROMs were defined at the midfoot, ankle, knee, and hip during both stair ascending and descending.

In each test session, corresponding ROM of the left and right leg were pooled for each athlete; thereafter, mean, variance, and the root mean square error (RMSE) were calculated for each ROM. The presence of homoscedastic differences was evaluated on a linear regression between the absolute individual differences and the corresponding mean of both sessions [11]. If less than 50% of the magnitude of the differences could be explained by the magnitude of the mean ($R^2 < 0.5$), homoscedasticity was accepted. If heteroscedasticity had to be assumed, a logarithmic transformation of the data was made, as suggested by [21], before calculating the limits of agreement.

To obtain the 95% limits of agreement for one variable, the standard deviation of all individual differences between the test sessions was multiplied by 1.96 [22]. To estimate possible dependency between changes in velocity or stride length and changes in investigated variables, a sign test ($p < 0.1$) was made.

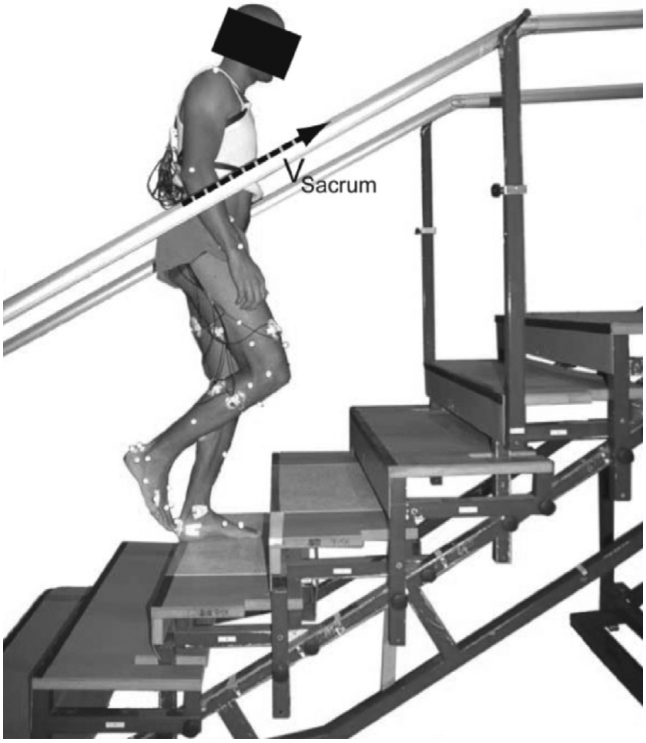


Fig. 1. The laboratory staircase of the study, and the definition of the velocity of the subject by tracking the spatial velocity of the sacrum marker.

The entire kinematic and statistical analysis was done with programs written in MATLAB (Mathworks Inc., Natwick, MA).

3. Results

The mean velocities were calculated from the spatial velocity of the sacrum marker, which ranged during both stair ascent and descent from 0.63 to 0.68 m/s. The movement velocity differed up to 0.06 m/s between the two test sessions (Table 1). None of the changes in the variables significantly depended on the changes in movement velocity.

The largest ROM were generally seen in the sagittal plane, in particular at the knee during stair descent (dn_k_flx, see Table 2), and at the knee and hip during stair ascent (up_k_ext, up_h_ext, see Table 2).

Considering both test sessions, calculated RMSE ranged from 0.8° to 3.9° of angular joint displacement. Corresponding RMSE of the first and second test session differed up to 1.1° (dn_h_ir). In 31 variables the difference was between 0.1° and 0.3° (see Table 2, fifth and sixth column).

The mean of the absolute difference between the sessions for each ROM was in 40 variables (out of 43 calculated) no larger than 0.4° (Table 2, seventh column). Similarly, the 95% limits of agreement of thirty ROM were equal or smaller than 3°, and in 13 ROM larger than 3° (Table 2, eighth column).

4. Discussion

Due to their dependence on the definition of the reference position, maximum and minimum angular displacements were not considered in the present study. In addition, since definition of timing variables is challenged if the angular displacement does not show a distinctive maximum/minimum, or shows more than one local maximum/minimum, they were not evaluated either.

The magnitudes of the ROM were in the order of prior published ranges of angular joint displacement during stair ambulation [23–25].

Discrete kinematic variables were investigated on sixteen healthy runners during barefoot walking and running in [4]. Regarding RMSE, the absolute mean differences between the mean ROM, and 95% limits of agreement, the results showed similar values to the present study. For example, the absolute mean differences between the mean ROM were commonly no larger than 0.5° compared to 0.4° in the present study, and the 95% limits of agreement were most frequently equal or smaller than approximately 3° in both studies.

Since other relevant studies on day-to-day consistency employed different statistical methods, further comparisons are biased. Instead, factors affecting consistency will be discussed.

None of the variables depended on a change in the movement speed. The effect of stair ambulation velocity on kinematic variables has not been systematically investigated. In level walking, only negligible changes have been observed due to a velocity change of 0.5–1 m/s [26,27]. Thus, we concluded that the observed velocity changes had only a minor impact on the day-to-day consistency. As opposed to a self selected velocity, a predefined movement velocity might cause a less consistent stair ambulation pattern because it may appear as unfamiliar for some subjects.

None of the subjects trained according to a specific training regimen that could have affected stair ambulation or had an injury between the test sessions. Therefore, the presented consistency of stair ambulation variables provides an appropriate basis for interpretation of intervention studies and for differentiation of gait patterns on stairs in the clinic.

Repeated marker placement will still influence the consistency, even if marker placement is based on a comprehensive protocol