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P Moretto, M Bisiaux, M A Lafortune. Froude number fractions to increase walking pattern dynamic similarities: Application to plantar pressure study in healthy subjects. *Gait & Posture*, 2006, 25, pp.40-48. <hal-04363905>

HAL Id: hal-04363905

<https://hal.science/hal-04363905v1>

Submitted on 26 Dec 2023

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Froude number fractions to increase walking pattern dynamic similarities: Application to plantar pressure study in healthy subjects

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Abstract

The purpose of this study was to determine if using similar walking velocities obtained from fractions of the Froude number (N_{Fr}) and leg length can lead to kinematic and kinetic similarities and lower variability. Fifteen male subjects walked on a treadmill at 0.83 (VS_1) and 1.16 m s⁻¹ (VS_2) and then at two similar velocities (V_{Sim27} and V_{Sim37}) determined from two fractions of the N_{Fr} (0.27 and 0.37) so that the average group velocity remained unchanged in both conditions ($VS_1 = \bar{V}_{Sim27}$ and $VS_2 = \bar{V}_{Sim37}$). N_{Fr} can theoretically be used to determine walking velocities proportional to leg lengths and to establish dynamic similarities between subjects. This study represents the first attempt at using this approach to examine plantar pressure. The ankle and knee joint angles were studied in the sagittal plane and the plantar pressure distribution was assessed with an in-shoe measurement device. The similarity ratios were computed from anthropometric parameters and plantar pressure peaks. Dynamically similar conditions caused a 25% reduction in leg joint angles variation and a 10% significant decrease in dimensionless pressure peak variability on average of five footprint locations. It also led to heel and under-midfoot pressure peaks proportional to body mass and to an increase in the number of under-forefoot plantar pressure peaks proportional to body mass and/or leg length. The use of walking velocities derived from N_{Fr} allows kinematic and plantar pressure similarities between subjects to be observed and leads to a lower inter-subject variability.

In-shoe pressure measurements have proven to be valuable for the understanding of lower extremity function. Set walking velocities used for clinical assessment mask the effects of body size and individual gait mechanics. The anthropometric scaling of walking velocities (fraction of N_{Fr}) should improve identification of unique walking strategies and pathological foot functions.

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Keywords: Walking; Froude number; Dynamic similarity; Joint angles; Plantar pressure

1. Introduction

Previous studies [1,2] reported inter-subject dynamic similarities during the transition from walking to running. The pendulum model was applied to set similar velocities between subjects (Fig. 1). The mass of the body at the centre

of gravity (Cg) oscillates at the end of a rigid segment length L representing the leg [3,4]. At the time of a step, Cg of the subject describes an arc of a circle of radius L . At the linear velocity (V), Cg undergoes an acceleration (\ddot{a}) equal to V^2/L . When the leg is vertical, \ddot{a} is directed upwards and perpendicular to the ground. This acceleration cannot be higher in intensity than gravitational acceleration (g) because the model would take-off. The take-off of the subject illustrates the disappearance of the double support phase and the transition from walking to running. The ratio (V^2/gL) enabled the authors to estimate a theoretical Froude

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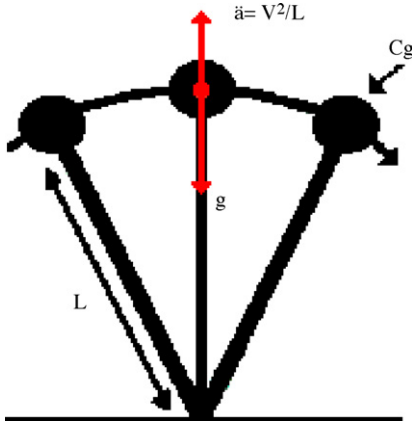


Fig. 1. Modeling of the transition between walking and running according to Alexander (1992). With \ddot{a} , acceleration; g , gravitational acceleration; C_g , centre of gravity; V , linear velocity; L , length of the leg.

number ($N_{Fr} = V/\sqrt{gL}$) equal to 1 [3,5] at the transition between walking and running.

Using Thorstensson and Roberthson's [6] experimental data, Alexander [2] and Donelan and Kram [7] estimated that this transition occurred at a N_{Fr} of approximately 0.6. Wagenaar and Beek [8] and Zatsiorsky et al. [9] went even further by saying that fractions of N_{Fr} below 1 can be used to determine similar walking velocities between different subjects. A recent review by Vaughan and O'Malley [10] presented studies which used the Froude number in naval architecture, for locomotion analysis and advancements in robotic science. From Alexander [5] to Zijlstra et al. [11], many studies have used the Froude number to differentiate between the effects of walking velocity and anthropometry.

However, many of these studies considered the Froude number (N_{Fr}) as the dimensionless walking speed and focussed on N_{Fr} as a means to normalise (set or spontaneously adopted) walking velocities. The use of the Froude number to determine similar dynamic conditions of walking has not been assessed.

Similar dynamic conditions suppose geometric similarities between different subjects. The first idea is to consider that two subjects are anthropometrically proportional. Two subjects (S_1 and S_2) being proportional, the ratios computed from the leg length (l_2/l_1) and body mass (m_2/m_1) are defined as k and k^3 , respectively [9]. In a wider sense, these ratios defined the length (L) and mass (M) basic dimension ratios.

Under similar dynamic conditions, the determining of similar velocities from N_{Fr} enables us to establish a time ratio (λ). Velocity is distance divided by time. The ratio of velocities is therefore equal to $k\lambda^{-1}$. To express the ratio of similar velocities (V_{Sim1} and V_{Sim2}) of the same two subjects, the constant N_{Fr} and g (gravitational acceleration) must be simplified. The velocity ratio is therefore equal to the square root of leg length ratio (Eq. (1)):

$$\frac{V_{Sim2}}{V_{Sim1}} = \frac{N_{Fr}\sqrt{gl_2}}{N_{Fr}\sqrt{gl_1}} = \sqrt{\frac{l_2}{l_1}} = k^{0.5} \quad (1)$$

Determining similar velocities between subjects means determining a time scale which is dependent on the distance scale. As the ratio of velocities ($k\lambda^{-1}$) is equal to $k^{0.5}$, consequently, the time ratio (λ) is equal to $k^{0.5}$.

Under similar conditions, the ratios of the basic dimensions, length (L), mass (M) and time (T) are k , k^3 and $k^{0.5}$, respectively. All the kinematic and kinetic ratios can be determined as a combination of the ratios of the basic dimensions. For example, the product of similarity ratios corresponding to each of the physical dimensions involved in pressure ($ML^{-1}T^{-2}$) expresses the pressure similarity ratio (Eq. (2)):

$$ML^{-1}T^{-2} \Rightarrow k^3 k^{-1} (k^{0.5})^{-2} = k \quad (2)$$

Therefore, ratio "k" can be computed from the ratio of the pressure peaks (PP_1 and PP_2) of two different subjects (S_1 and S_2), i.e. $k = PP_2/PP_1$.

If the dynamic conditions associated with walking velocity are similar, then the kinematic and kinetic parameters should be proportional from one subject to another. An exception exists, as the angles cannot be directly expressed from basic dimensions and the trigonometric functions are necessary to establish the link between lengths and angles. However, the effect of dynamic similarities on angles can be developed thus.

According to the inverted pendulum model, linear velocity (V_{Sim}) of body mass at the centre of gravity swinging at the extremity of a leg of length (l) can be expressed in relation to the angular velocity (ω) (Eq. (3)). Angular velocity (ω) is the ratio of an angle (θ) and time (Δt):

$$V_{Sim} = l\omega = l\theta\Delta t^{-1} \quad (3)$$

The ratio of similar velocities, V_{Sim1} and V_{Sim2} , of the two subjects, S_1 and S_2 , is equal to $k^{0.5}$ and can be expressed in terms of leg lengths (l_2 and l_1), angles (θ_2 and θ_1) and times (Δt_1 and Δt_2) (Eq. (4)):

$$\frac{V_{Sim2}}{V_{Sim1}} = \frac{l_2\theta_2\Delta t_2^{-1}}{l_1\theta_1\Delta t_1^{-1}} = k\alpha k^{-0.5} = k^{0.5} \Rightarrow \alpha = 1 \quad (4)$$

Since the angle ratio (α) is equal to 1 if the angles θ_2 and θ_1 are identical (Eq. (4)), it follows that kinematic similarities should yield identical joint angles between one subject and another at "Similar" velocities.

Being normalised with respect to L , M , T dimensions, the peak of pressure (corresponding to a force ($kg\ m\ s^{-2}$) distributed over a surface (m^2)) can be expressed in a dimensionless form as: $Dim(PP) = PP\ SL^2/mg$ (PP , peak of pressure (kPa); SL , step length (m); m , body mass (kg) and g , acceleration due to gravity ($m\ s^{-2}$)). The dimension of $Dim(PP)$ is 1 ($\frac{kg\ m\ s^{-2}}{m^2} \frac{m^2}{kg\ m\ s^{-2}}$).

According to Stansfield et al. [12], the step length rather than leg length is used to introduce a 'velocity-dependent' parameter in the dimensionless expression of a pressure

peak. Under similar dynamic conditions, the Dim(PP) of different subjects is theoretically unique. Under experimental conditions, a decrease in the inter-subject variability of Dim(PP) is expected as an effect of the determination of similar dynamic conditions using the Froude number fractions.

Determining similar velocities should help to pinpoint similarities studied from the joint angles, dimensionless peaks of pressure and the similarity ratios of anthropometric parameters and pressure peaks. The purpose of the present study is to determine whether “Similar” velocities determined from fractions of the Froude number, lead to greater inter-subject walking pattern similarity.

2. Materials and methods

2.1. Subjects

Fifteen male volunteers participated in this study. They were healthy, free of foot abnormalities and had not undergone leg or foot surgery during the previous 2 years. The left leg length was measured in standing position between the greater trochanter and the floor using a meter. The subjects’ mean age, mass, height and leg length were 23.4 years (S.D. 4.8), 77.5 kg (S.D. 9.8), 1.83 m (S.D. 0.55) and 0.98 m (S.D. 0.22), respectively.

2.2. Determining “Similar” velocities

To determine velocity, we devised two conditions that we called “Set” and “Similar”. In the former, two velocities were imposed on the subjects, the first of which was set arbitrarily at 0.83 m s^{-1} (VS_1) and then increased by 40% to define VS_2 (1.16 m s^{-1}).

From VS_1 and VS_2 , two mean values of the Froude number were computed (Eqs. (5) and (6)):

$$\overline{N_{Fr1}} = \sum_{i=1}^n \frac{VS_1}{\sqrt{gl_i}} \frac{1}{n} = 0.27 \quad (5)$$

$$\overline{N_{Fr2}} = \sum_{i=1}^n \frac{VS_2}{\sqrt{gl_i}} \frac{1}{n} = 0.37 \quad (6)$$

In these equations, l_i represents the individual subject leg length, g the gravitational acceleration and n the number of subjects.

The “Similar” velocity conditions (V_{Sim27} and V_{Sim37}) for each subject were calculated using Eqs. (7) and (8):

$$V_{Sim27} = 0.27 \sqrt{gl_i} \quad (7)$$

$$V_{Sim37} = 0.37 \sqrt{gl_i} \quad (8)$$

Through this process, the means of the individual similar velocity conditions are kept equal to the set velocity conditions ($VS_1 = \overline{V}_{Sim27}$ and $VS_2 = \overline{V}_{Sim37}$).

2.3. Protocol

The subjects performed the walking trials at “Set” (VS_1 and VS_2) and “Similar” (V_{Sim27} and V_{Sim37}) velocities on a “Marquette Electronique MTC-1” treadmill. First, the subjects spent 20 min familiarizing themselves with the different walking velocities. During the tests, the recordings of the video sequences and plantar pressure measurements of eight randomised consecutive steps were taken after 2 min of walking, thus allowing for gait pattern stabilization [13]. The recordings were started using a remote control to synchronize both measurements.

2.4. Material

2.4.1. The optoelectronic system

For the kinematic analysis, markers were placed on the left lateral malleolus, femoral condyle and greater trochanter to obtain a model of the lower limbs in the sagittal plane [14]. Two additional markers were placed at the front and back of the shoe. All subjects wore the same type of footwear. The coordinates of the body landmarks were collected at 50 fps using a CCD camera (Sony XC-75CE) mounted orthogonally to the walking direction, 80.5 cm above the ground and 12 m away from the motion plane. Camera range for full view of test was $2 \text{ m} \times 2 \text{ m}$. The film data were obtained by digitizing each film frame with an image-capture board (Matrox Meteor, Dorval, PQ, Canada) interfaced with image analysis software (Noesis, Les Ulis, France). The position data were filtered using a fourth-order Butterworth filter [15] whose best cut-off frequency was found to be 6 Hz. Hence, the root mean square (RMS) errors relative to the segmental lengths were 8% lower for the foot and 5% lower for the other segments after filtering. Knee and ankle angles were then computed from the digitised limb coordinates.

2.4.2. The plantar pressure measurement

The plantar pressure measuring system (Parotec, Paromed GmbH, D-8201, Neubeuern, Germany) comprises two insoles connected to a waist-mounted unit. The insoles are equipped with 16 separate and integrated hydrocell sensors sized from 1.21 to 4.10 cm^2 depending upon the footprint locations and the sole sizes. The hydrocell consists of an electronic element (Wheatstone bridge) enclosed in a capsule filled with an incompressible fluid. Our own calibration for each sensor confirmed previous data [16,17] and showed measurement range from 0 to 625 kPa, accuracy of $\pm 2.0\%$ of full scale, precision of $\pm 0.4\%$ of full scale and negligible hysteresis (0.05% at 200 kPa).

Sensors were grouped according to eight predefined foot areas [18]. The sampling rate was set at 100 Hz.

2.5. Variables

2.5.1. Kinematic similarities

The step time was defined by two consecutive left heel strikes. The data time was then reported for the shorter step time recorded at 50 fps. This being 820 ms, it induced a 41-point data normalisation. The knee and ankle patterns of eight consecutive steps were thus expressed as a function of step time percentage. The assumption underlying the ‘‘Similar’’ velocity approach implies a reduction of the difference among a group of subjects. Therefore, the inter-subject coefficient of variability of joint angles was chosen to test this assumption at both ‘‘Set’’ and ‘‘Similar’’ velocities. The joint angle variability was studied at each of the 41 percentages of the normalised step time.

2.5.2. Kinetic similarities

The dimensionless peaks of pressure (Dim(PP)) were computed from the pressure peaks recorded under the eight footprint locations. The Dim(PP) standard deviations were chosen to test both ‘‘Set’’ and ‘‘Similar’’ velocities effects on the variability.

The similarity ratio (k) was computed from each measured parameter: leg length (l), body mass (BM), and the pressure peaks (PP) of eight footprint areas. The 15 subjects were classified by order of increasing leg length. The similarity ratios were computed for each subject pair combination with reversed ratios avoided. Hence, the number of similarity ratios rose to 105 ($C_{15}^2 = 105$). Table 1 summarizes the unities, the dimensions, the similarity ratios and the ‘‘ k ’’ ratios expressed from the parameters assessed.

2.5.3. Statistical analysis

The Fisher–Snedecor F -test enabled analyses of ankle and knee angle ratios of variance observed in the ‘‘Set’’ and ‘‘Similar’’ conditions. It was repeated at each of the 41 percentages describing the normalised step time. The same test enabled analyses of Dim(PP) variability observed in both experimental conditions.

To verify the existence of dynamical similarities, we had to verify that the similarity ratios computed from leg length, body masses and plantar pressure peaks were equal. We considered that this equality was verified when the data variances and means did not significantly differ and that the anthropometric and kinetic similarity ratios were

significantly correlated. The statistical analysis was conducted thus: (i) a χ^2 -test enabled verification of the distribution normality of the different data; (ii) the ‘‘parameter’’ factor enabled us to differentiate the similarity ratios computed from leg lengths, body masses and plantar pressure peaks. A repeated-measure factor analysis of variance (ANOVA) detected differences associated with the factor ‘‘parameter’’ at each velocity. The Scheffe test for paired variables more precisely identified the significant differences observed between each of the similarity ratios and the ratios of leg lengths and body masses; (iii) a Fisher’s ‘‘ z ’’ coefficient of correlation between the different ratios themselves refined the analysis. Our conclusion derived from this three-step analysis was that dynamic similarities exist when the kinetic parameters were proportional to leg lengths and/or body masses.

The significance threshold was set at $P < 0.05$ for all the analyses.

2.6. Results

2.6.1. Kinematic variables

Figs. 2 and 3 present angular change in ankle and knee in terms of step percentage recorded at VS_1 versus V_{Sim27} and VS_2 versus V_{Sim37} , respectively. At ‘‘Similar’’ velocities (V_{Sim27} and V_{Sim37}), coefficients of variation of ankle and knee joint angles were significantly lower by 15–35% than those observed at the ‘‘Set’’ velocities (VS_1 and VS_2) (Figs. 2 and 3).

2.6.2. Kinetic variables

Fig. 4 presents the dimensionless pressure peaks (Dim(PP)) observed under the eight footprint areas at VS_1 versus V_{Sim27} and VS_2 versus V_{Sim37} . The Dim(PP) standard deviations significantly decreased by 11.16% on average for five locations (VS_1 versus V_{Sim27}) and by 10.12% on average for six locations (VS_2 versus V_{Sim37}).

2.6.3. Anthropometric similarities

The ratios computed from the heights 0.97 m (S.D. 0.03 [from 0.90 to 1.07]), the leg lengths 0.95 m (S.D. 0.03 [from 0.87 to 1]) and the masses 0.98 kg (S.D. 0.05 [from 0.87 to 1.12]) were correlated and define the anthropometric similarities of the subjects. The correlation coefficients between leg length and height ratios then between leg length and mass ratios were 0.83 and 0.5, respectively.

Table 1
Dimension and ratio of parameters studied

	Unit	Mechanical physical dimensions	Similarity ratios	k
Leg length (l)	m	L	k	l_2/l_1
Body mass (BM)	kg	M	k^3	$(BM_2/BM_1)^{1/3}$
Time (t)	s	T	$k^{0.5}$	$(t_2/t_1)^2$
Pressure peak (PP)	kPa	$ML^{-1}T^{-2}$	k	PP_2/PP_1

The ‘‘ k ’’ ratio has been computed for each subject pair combination with reversed ratios avoided. The example corresponds to the ratio of the parameters of one pair of subjects S_1 and S_2 .

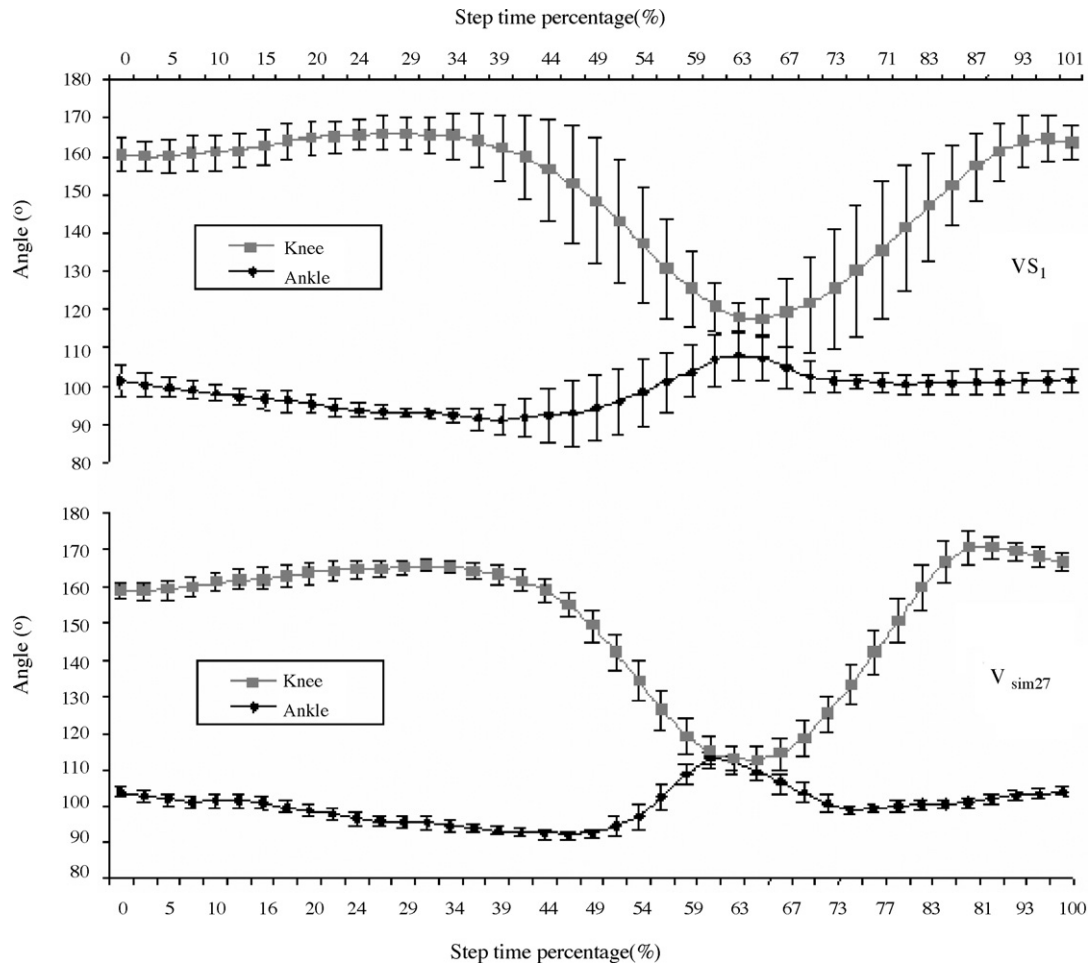


Fig. 2. Change in ankle and knee angles in terms of step time percentage in the VS_1 “Set” and V_{Sim27} “Similar” conditions. At each step time percentage, the coefficients of variation were significantly lower under similar conditions (V_{Sim27}) than under set conditions (VS_1) ($P < 0.05$). Reported data are mean and standard deviation.

2.6.4. Plantar pressure distribution dynamic similarities

Fig. 5 presents the “ k ” ratios expressed from pressure peaks of the eight footprint areas. Only the ratios that can be considered as equal to leg length and body mass ratios are retained.

2.6.5. Similarities observed at VS_1 versus V_{Sim27} (Fig. 5A)

At a “Similar” velocity (V_{Sim27}) similarities were found under the medial and lateral heel and under midfoot. Pressure peaks were proportional to body mass. Pressure peaks recorded under the fourth and fifth metatarsal heads were proportional to leg length at VS_1 and to body mass at V_{Sim27} . Under the second and third metatarsal heads, pressure peaks were proportional to mass and to leg length with no difference being observed between VS_1 and V_{Sim27} . At V_{Sim27} , the pressure peak under the first metatarsal head was proportional only to leg length whereas it was proportional to mass and leg length at VS_1 . Pressure peaks recorded under the medial midfoot and the Hallux were not proportional to mass or to leg length.

2.6.6. Similarities observed at VS_2 and V_{Sim37} (Fig. 5B)

When average velocity increased by 40% (0.83 m s^{-1} versus 1.16 m s^{-1}), the plantar pressure proportions to body mass and leg length increased at “Similar” velocity (V_{Sim37}). No other difference was observed between VS_2 and V_{Sim37} . Pressure peaks under the fourth and fifth metatarsal heads were found to be proportional to mass at V_{Sim37} whereas the pressure peak under the first metatarsal head, initially proportional to mass at VS_2 , was proportional to leg length at V_{Sim37} . The pressure peak under the Hallux was not proportional to mass or to leg length whatever the velocity.

3. Discussion

Clinicians studying pathological walking are often confronted with the problem of high inter-subject variability when comparing a patient’s walking pattern with a normal pattern. Using ankle and knee joint angles to detect spasticity-related differences in motor behaviour, Kelly

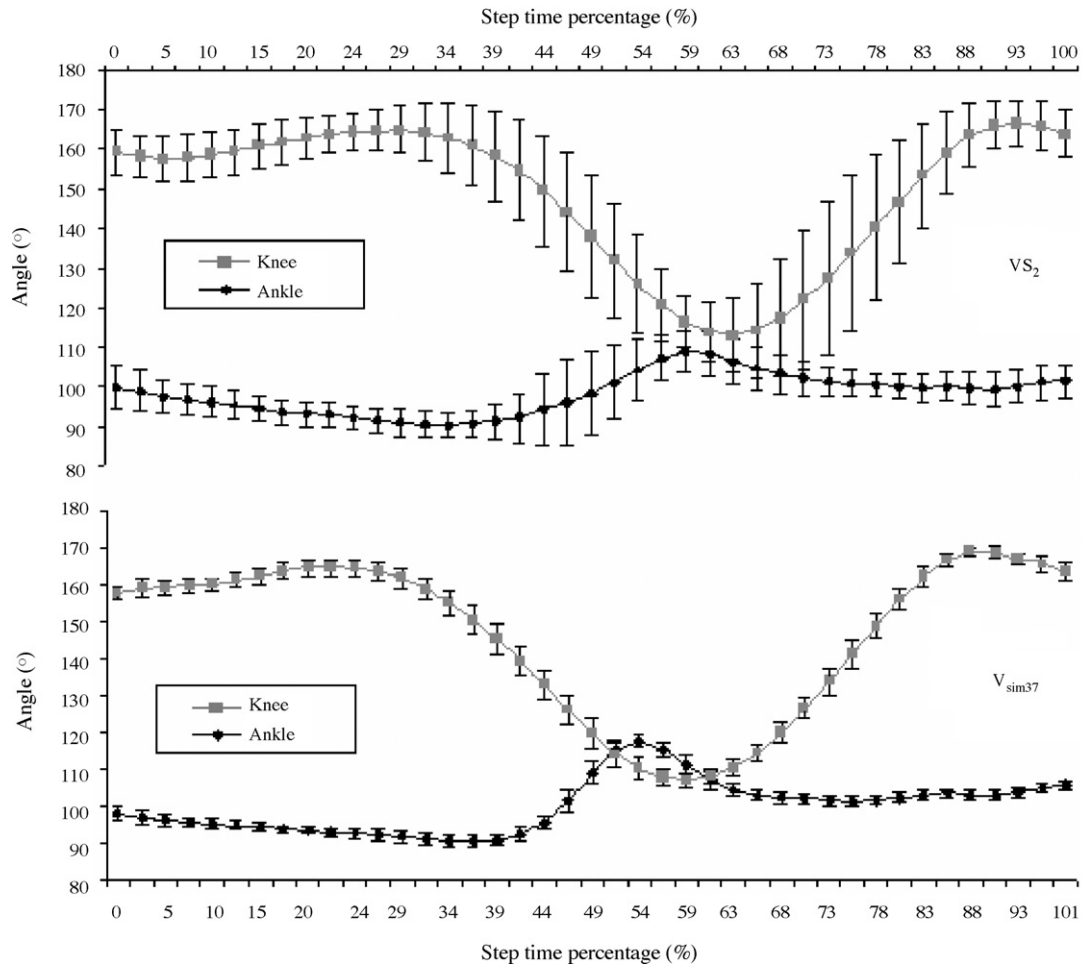


Fig. 3. Change in angles of ankle and knee in terms of step time percentage at VS_2 “Set” and V_{Sim37} “Similar” conditions. At each step time percentage, the coefficients of variation were significantly lower under similar conditions (V_{Sim37}) than under set conditions (VS_2) ($P < 0.05$). Reported data are mean and standard deviation.

et al. [19] were limited by the database’s large standard deviation affecting the differentiation between spastic disorders of different origin. Likewise, McPoil and Cornwall [20] abandoned the use of the centre of pressure path as a means of gauging the efficacy of foot orthoses because of its high variability (ranging from 43.4% to 48.6%).

As extensive research has shown, natural velocity is affected by numerous intrinsic and extrinsic factors [21,22]. The use of natural velocity in studies may contribute to the variability of biomechanical parameters reported in the literature. The purpose and the originality of the present study were to test a method of decreasing the walking pattern inter-subject variability and verifying its influence on plantar pressure similarities and inter-subject variability.

The study compared walking pattern similarities while subjects moved at the same velocity (Set conditions VS_1 and VS_2) and then at “Similar” velocities (V_{Sim27} and V_{Sim37}). The latter was measured from each subject’s leg length and from two Froude number fractions. In theory, the inter-segment angles of anthropometrically proportional subjects moving at “Similar” velocities should be identical. In

practice, angle variance observed at “Similar” velocities (V_{Sim27} and V_{Sim37} ; Figs. 2 and 3) is, on average, 25% lower than that observed in VS_1 and VS_2 “Set” conditions. It would seem that when Froude number fractions are used to determine velocities, inter-segment angles of subjects are closer and, therefore, kinematic similarities are better. These results can be compared with those Diedrich and Warren [23] who identified significant reductions in inter-segment angle variability during transition from walking to running at an N_{Fr} of 0.6. Our study on “Similar” walking velocities determined from Froude number fractions found similarities at velocities below this transition. As the kinematic findings demonstrated inter-subject similarities, plantar pressure distribution repercussions were expected. They would be contingent on anthropometric characteristics of the subjects and similar dynamic conditions linked to the way V_{Sim27} and V_{Sim37} velocities were determined.

Ratios computed from leg length and body mass were correlated. However, the 0.5 correlation found between leg length and mass ratios highlights the limitations of the initial assumption that our subjects were anthropometrically

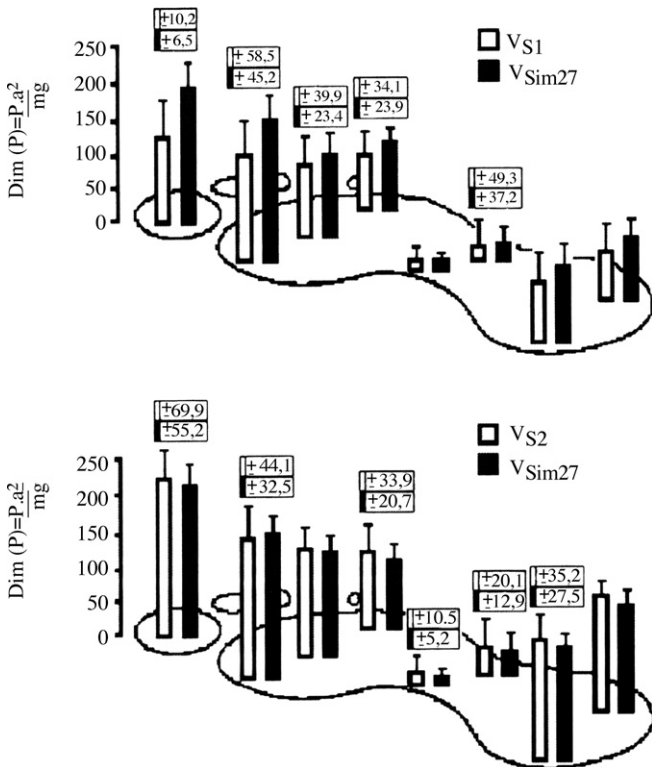


Fig. 4. Dimensionless pressure peaks. Text boxes indicate Dim(PP) standard deviations. They are mentioned when the variability between “Set” and “Similar” conditions is statistically significant ($P < 0.05$).

proportional. The ratios computed from pressure peaks varying between 0.65 and 1.74, significant correlation coefficients from 0.21 to 0.49 ($P < 0.05$) were considered to compensate for a low range of ratio values. These correlations between leg length (or mass) ratios and peak

pressure ratios enabled us to check that anthropometric and kinetic ratios were equal and to put forward the idea of the existence of pressure peaks proportional to body masses and/or to leg lengths. This assumption is supported by the decrease in dimensionless peak pressure variability under the same footprint locations. However, the correlation between the anthropometric ratios suggests random relations between peak pressure and leg length or body mass.

3.1. Dynamic similarities under ‘heel’

No pressure peak was proportional to body mass or to leg length under lateral or medial heel at VS₁ (Fig. 5), confirming Shorten et al. [24] who found no significant correlation between heel pressure peak and subject mass during a study where the same velocity was imposed on several subjects.

Conversely, determining “Similar” velocities generates under-heel pressure peaks proportional to mass (V_{Sim27}; Fig. 5). These kinetic observations confirm kinematic findings. During the loading phase (0–30% of step time) coefficients of variation of angles recorded at ankle and knee were found to have decreased by 15% on average at V_{Sim27} and V_{Sim37} compared with “Set” conditions. The Dim(PP) variability decreases under these locations and the standard deviation difference reaches a significant –8.7% value under the lateral heel at V_{Sim37} compared to VS₂. Pressure peaks were mostly proportional to mass. According to Morag and Cavanagh [25], the main factors for determining under-heel pressure peaks were the mechanical characteristics of the heel pad soft tissue, age, the longitudinal structure of the plantar arch and the kinematics of the leg during heel strike. In our study, only the characteristics of the

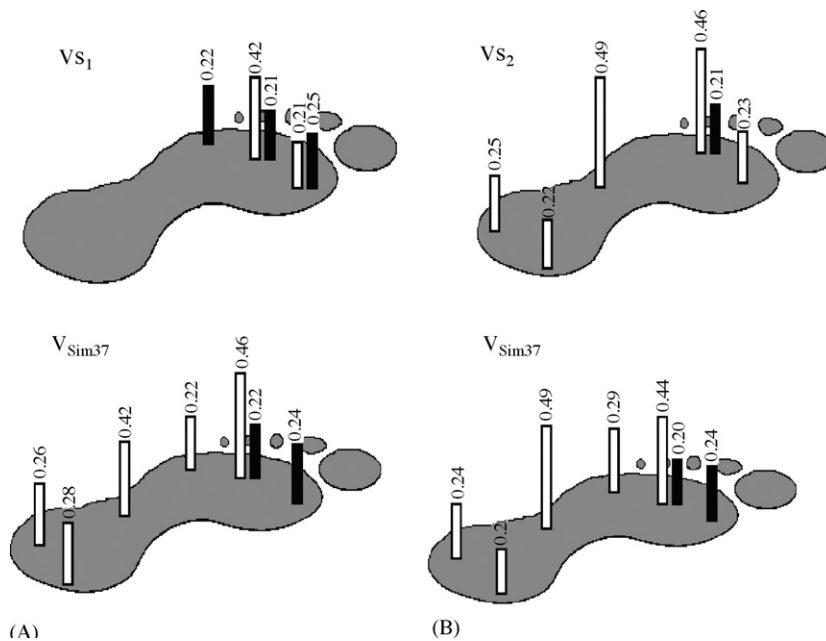


Fig. 5. Pressure peak similarity ratios recorded under the eight footprint areas in the “Set” (VS₁ and VS₂) and “Similar” (V_{Sim27} and V_{Sim37}) conditions. Only the ratios significantly correlated to leg length (■) and body mass (□) ratios are presented ($P < 0.05$).

heel pad were not checked. Our subjects were all of similar age, subjects with flat or high arch feet were not selected, leg kinematics in similar conditions showed inter-subject similarities. The peak pressure similarities observed under the heel at V_{Sim27} and V_{Sim37} appeared to be due to the determination of similar walking velocities.

3.2. Dynamic similarities under ‘midfoot’

Results under midfoot were less straightforward. Where coefficients of variation of ankle and knee angles decreased by 35%, on average, at “Similar” velocities during the single support phase (30% and 60% of step time), the number of similarity ratios under lateral and medial midfoot areas increased, though only at the slower velocity (V_{Sim27}). At V_{Sim37} , the number (of similarity ratios) was identical to that observed at VS_2 . Peak pressures were mainly proportional to body mass in both cases (VS_2 and V_{Sim37}). However, the standard deviation of Dim(PP) observed in similar conditions (V_{Sim27} and V_{Sim37}) significantly decreased by 5.3% under the lateral midfoot and by 12% under the medial midfoot compared to “Set” conditions. The study of angle and pressure peaks variations showed good inter-subject similarities and confirmed that determining “Similar” velocities improved midfoot pressure similarities (Figs. 4 and 5).

3.3. Dynamic similarities under ‘forefoot’

During the push-off phase, determining “Similar” velocities brought about a 30% decrease in inter-leg angle variation. However, the method failed to increase the number of peak pressure similarity ratios under the forefoot. Pressure peaks under the metatarsal heads were closely linked to movements of the ankle and foot joints and to EMG activity in the gastrocnemius. Under-Hallux pressure peaks were associated with the structure and mobility of the first metatarsal joint [24]. These different observations indicate the complexity of the factors involved in determining pressure peak under this area. With the occurrence of a pressure peak proportional to body mass under M4-5 at V_{Sim37} , it becomes apparent that determining “Similar” velocities does indeed improve forefoot similarities but only at the higher velocity. The expected effect on Dim(PP) variability is stronger and similar conditions lead to a decrease in the standard deviation of 10.2% under the fourth to fifth metatarsal heads between VS_1 and V_{Sim27} and of 14.7% under the Hallux between VS_2 and V_{Sim37} .

Determining walking velocity using Froude number fractions does generate similar walking patterns that lead to lower kinetic and kinematic variations and greater similarities between different subjects. Studying peak pressure under eight footprint areas has shown that determining “Similar” velocities greatly improves under-heel similarities though somewhat less so under the forefoot. The complexity and mobility of the bone structures under the forefoot could explain the differences in plantar pressure

distribution between subjects during the push-off phase. However, the variability of the dimensionless pressure peaks is significantly lower in “Similar” conditions. This observation concerns all the footprint areas and confirms that the inter-subject variability is partly linked to poor dynamic similarities induced by the “Set” conditions.

4. Conclusion

This study demonstrated that the determination of walking speeds using Froude number fractions below one is a successful method to establish dynamic walking similarities between different subjects. It could be used, for example, when a low inter-subject variability is expected to define a data base of biomechanical parameters. Several studies demonstrate that the parameter variability induced by spontaneously chosen walking speed is a limit to the detection of patient characteristics [26–28]. Van der Linden et al. [29] or Wagenaar and Beek [8] compared the patients to healthy results at the same dimensionless walking speed to differentiate between effects caused by speed and underlying pathology. This study suggests a dimensionless database constructed for a healthy population walking at different Froude number fractions that should enable a decrease in the biomechanical parameter variability and allow easier identification of patient characteristics. The dimensionless results of a patient walking at self-selected walking velocity could thus be compared to those of the database obtained from healthy subjects walking at the same dimensionless walking speed, i.e. at the same Froude number fraction.

This database should be constructed from healthy subjects selected on the basis of their anthropometric similarities to avoid the difficulty in observing proportionality to length and mass. Further studies should be conducted to explore the accuracy of a dimensionless database and to test its usefulness in differentiating ‘abnormalities’ due to anthropometric variation, such as obesity.

Acknowledgements

Financial support was given by the Conseil Regional Nord-Pas de Calais, the Delegation Regionale à Recherche et à la Technologie du CHRU and the Institut Regional de Recherche sur le Handicap of Lille. The authors would like to thank M. Holvoet and Prof. Pelayo for helpful comments about video analysis and drafts of the manuscripts, respectively.

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