Quantitative Analysis of Rotational Movements of Knee in Healthy Subjects During Treadmill Barefoot Walking

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Abstract: *Background and Purpose*: Cinematic analyses of human walking are widely carried out, but the assessment of sex-related differences is still incomplete. Knee range of motion was investigated in healthy sedentary subjects during standardized speed treadmill walking.

Subjects and Methods: One hundred and three subjects aged 20-79 years were filmed by an optoelectronic system. Three-dimensional knee joint angular data were obtained from trajectories of markers using Euler operators.

Results: On average, within sex, flexion-extension and internal-external rotation were symmetric (Watson-Williams' test, $p > 0.05$). During walking, women had a larger knee flexion-extension (mean 67.5°, SD 0.8°) than men (mean 64.8°, SD 0.8°, $p < 0.05$), but similar internal-external rotation (women, 22.6°, SD 0.6°; men, 21.2°, SD 0.5°). No significant correlations between movements and age or anthropometric characteristics were found.

Conclusions: In healthy sedentary adults, treadmill walking is performed with knee range of motion that is largely independent from age, sex or anthropometry.

Keywords: Movement analysis, cinematics, knee, range of motion, treadmill, walking gait.

INTRODUCTION

Walking is one of the basic motor functions of humans. Technological evolution has provided instruments for the study of human and animal movements. Currently, the most up-to-date technology consists in video-based optoelectronic stereophotogrammetric systems (OSS) [1,2]. OSS are similar to binocular human vision and provide real-time quantitative analysis of movement. OSS allow the assessment of both overground and treadmill walking [3-5].

Cinematic analyses of human locomotion are widely carried out in clinical and research laboratories [6-8]. Indeed, data referred to frequency, length and width step [5, 9], to knee torque and to sex-related differences during overground barefoot walking [6, 7], and to age-related differences in overground velocity [10, 11], are available. Overall, overground walking is considered more natural; its assessment may provide data with an easier practical application.

In contrast, no detailed analyses on the effects of sex, age and anthropometry were made for treadmill walking, and the quantitative assessment of this kind of gait is still incomplete.

The aim of this preliminary study was to investigate differences in gait between healthy men and women during treadmill barefoot walking at standardized speed. In particular, in the current report a simplified knee range of motion (ROM) protocol was assessed during treadmill walking.

The current widespread use of treadmills within fitness and wellness programs, as well as at home and during rehabilitation, focused the investigation about the knowledge of age-, sex- and anthropometry- related characteristics of lower limb motion during this kind of gait.

The results may provide useful hints for treadmill use: if significant effects of sex, age or anthropometry would be found, more information for the definition of specific rehabilitative and fitness protocols may be obtained.

MATERIALS AND METHODOLOGY

Subjects

One hundred and three healthy adults (57 men and 46 women) aged 20-79 years volunteered for the study after a detailed explanation of the procedures and possible risks involved. The subjects were students and staff attending the Department of Human Morphology of Milan University; friends and relatives of investigators were also recruited. All subjects were sedentary; none of them was or had been involved in sports at professional level.

They were examined by a clinician and found to be in good general health, free from present or past problems to the lower limb joints; all of them had a right foot dominance [12].

Standing height (m) and body mass (kg) were measured in each subject, and Body Mass Index (BMI, the ratio of body mass to squared standing height, kg/m^2) was calculated (Table **1**). Approval was obtained from the local Ethics Committee prior to commencement (all procedures were not invasive and not potentially harmful). After describing the nature/characterstics and possible risks of the study completely, written informed consent was obtained from each participant.

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1874-3870/08

Table 1. Anthropometric Data of the Analyzed Subjects

	Age (Years)		Body weight (Kg)		Standing height (m)		BMI (Kg/m^2)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Men N = 57	30	15	73.4	12.1	1.75	0.07	23.76	3.01
Women N = 46	33	13	59.0	7.9	1.66	0.06	21.46	2.55
P value	NS		p<0.001		p<0.001		p<0.001	

Statistical comparison made by Student's t-test for independent samples (NS, not significant, $p > 0.05$). BMI: body mass index.

Instrumentation

Cinematic data were collected using a video-based motion analysis system (SMART, BTS Milano, Italy) with six cameras operating at a sampling rate of 120 Hz. In this way the three-dimensional position of markers fixed to body segments was collected.

The study required the use of a motorized treadmill with handrails and a belt walking area of 125 x 41 cm (525ex, Pro Form, Canada), driven by an electric motor of 1.8 kW.

Frame Definition

Three-dimensional knee joint angular cinematic data were obtained after tracking and analysing procedures on the trajectories of spherical retro-reflective markers (10 mm diameter). A simple set of markers was used. In particular, markers were mounted over four flat plastic mono-blocks arranged on the legs and thighs with adjustable elastic tapes, with a technical protocol similar to that adopted by other authors [13]. To limit movement artefacts, the elastic tapes were put 1.5 cm below the anterior tibial prominence and 3 cm over the patella with the lower limbs in complete extension.

For each mono-block, three markers allowed the determination of a single plane referring to each of the four bone segment (right and left thigh and leg, Fig. (**1**)). These markers allowed the reconstruction of cluster technical frames (CTF) embedded in each support of the body segments [14, 15].

The cameras defined a working volume of 88 (width) x 132 (height) x 121 (depth) cm. Metric calibration and automatic correction of optical and electronic distortions were performed before each acquisition session, giving a static accuracy of 0.02% on a 40 cm long wand.

Experimental Procedures

All subjects were provided of shorts, to allow an easier positioning of marker mono-blocks (Fig. **1**), and sport socks, to uniform the walking phase and to avoid the influence of different kinds of shoes.

The protocol required a period of 5-10 minutes of training on the treadmill, which varied according to the individual

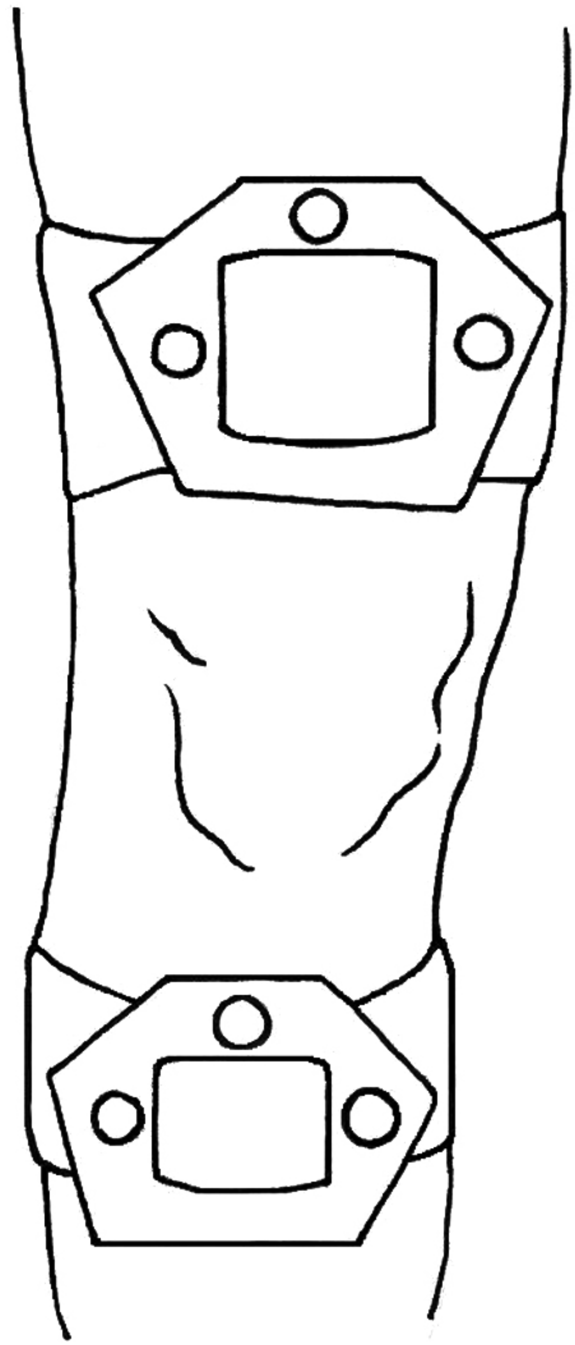

Fig. (1). The clusters marker rigid blocks fixed on the thigh and leg.

previous experience [4]. In this way, each subject gained sufficient control to walk skilfully on the treadmill [16]. Each participant confirmed the individual acclimatation.

Immediately after, the same experimenter positioned all markers, and a static acquisition (lower limb in extension) was made to provide a reference position of the marker clusters.

At the established signal each subject switched-on the treadmill and began walking to comply the belt movement and without holding the handrails. The subjects were asked to look straight ahead, no restrictions about movements were imposed and arm swing was allowed. Treadmill inclination was set at 0°. The speed was set at 1.0 m/sec, considering the optimal speed of walking with minimal metabolic cost [17], and after 30 sec (the minimum time needed to reach the fixed speed by the belt), six right and six left walking phases were captured [18].

For each subject and repetition, a preliminary qualitative control verified the path of motion of each movement. The subjects did not reported discomfort during or after the completion of a walking trial in any case.

Data Analysis

To estimate knee joint ROM, we considered the segments like a cinematic chain of links. Each bony segment was considered non-deformable and was represented using rigid bodies [1].

After the *tracking* phase that provided the x, y, z coordinates of each marker, original computer software used them to determinate, frame by frame, the plane of body segment. Euler angles mathematical operators were used to define the three-dimensional angular motion of joints [19-21].

In particular, the flexion-extension motion and the internal-external rotation (movements allowed by the knee joint) of the leg relative to the thigh were calculated. The first motion occurred about the medial-lateral axis attached to the proximal segment, and the second one about its longitudinal axis [22]. A graphic subroutine allowed the qualitative control of the performance of each movement. Data in the sagittal (flexion-extension) and horizontal (internal-external rotation) planes were analyzed throughout the six steps separately for each side. From the six angular data, mean values were then obtained for each side.

Statistical Analysis

Mean and standard deviation were computed separately for men and women, side and rotation. Bivariate variables (angle data) were analyzed by using the rectangular components of the angles (sine and cosine). Differences in univariate data were assessed by Student's t-test for independent samples, while for bivariate data Watson-Williams' test was used. A post-hoc assessment of the power of the statistical tests was made using the non-central F-distribution as reported by Pearson and Hartley [23].

Linear correlations between age, anthropometric values (weight, height, BMI) and knee range of motion were made. The level of significance (alpha level, type I error) was set at 5% for all comparisons ($p < 0.05$). The beta level (type II error) was set at 90%.

Error of Method

The validity of the procedure was tested by duplicate acquisitions in 15 subjects (5 men and 10 women). Data obtained in the repeated assessments, separately for men and women within side and rotation, were compared by computing the technical error of measurement (random errors, TEM $= [\Sigma\ (D^2)/\ 2 \times N]^{0.5}$, where D is the difference between the two repeated measurements, and N is the number of subjects), and by paired Student's t (systematic errors).

For random errors, the error percentage was calculated as the percentage ratio between squared TEM and the sample variance. The largest error percentages were 5.35% in men and 2.13% in women, respectively for right and left internal-external rotation.

No systematic errors were found ($p > 0.05$ for both sexes, sides and plane of movement).

RESULTS

On average, men were significantly taller, heavier and had a greater BMI than women, but they had similar mean ages (Table **1**, Student's t-test for independent samples).

Descriptive statistics of ROM for each sex and side are reported in Table **2**. On average, within sex, knee flexion-extension and internal-external rotation during treadmill walking were symmetric ($p > 0.05$, Watson-Williams' test). Left and right angular data were further pooled within sex. Statistically significant differences between men and women (Watson-Williams' test, $p < 0.05$) were found for knee flexion-extension: women, mean 67.5°, SD 0.8°; men, mean 64.8°, SD 0.8°. In contrast, no significant sex-related differences were found for internal-external rotation (women, 22.6°, SD 0.6°; men, 21.2°, SD 0.5°).

A post-hoc power assessment of the statistical tests found that in all occasions the power was larger than 0.99, thus indicating that the analyses had negligible type II errors.

In both sexes, all correlation indexes between flexion-extension and internal-external rotation (left and right side separated), and age or anthropometric characteristics were not significant ($p > 0.05$), with correlation coefficients next to zero (Table **3**).

DISCUSSION

The quantification of the angular range of motion relative to a daily action can provide useful reference values to be

Table 2. Knee Range of Motion During Treadmill Walking

	Women				Men			
	Flexion-Extension		Internal-External Rotation		Flexion-Extension		Internal-External Rotation	
	Right	Left	Right	Left	Right	Left	Right	Left
Mean	67.8	67.1	22.9	22.3	64.8	65.2	22.9	20.1
SD	1.1	1.2	0.7	1.0	1.2	1.1	0.9	0.7
P value	NS		NS		NS		NS	

All values are degrees. Statistical comparison: Watson-William's test (NS, not significant, p>0.05).

Table 3. Linear Correlation Analyses Between Knee Range of Motion During Treadmill Walking (Y) and Age/Anthropometric Data (X) of the Analyzed Subjects

		Flexion-Extension			
		Women		Men	
		Right	Left	Right	Left
Age	R^2	0.027	0.007	0.046	0.074
		0.09 x + 64.31	0.05 x + 65.15	0.14 x + 58.58	0.18 x + 59.42
Body weight	R^2	0.035	0.018	0.035	0.027
		-0.17 x + 77.49	-0.14 x + 75.39	-0.16 x + 75.18	-0.14 x 75.95
Standing height	R^2	0.020	0.008	0.066	0.031
		-0.18 x + 96.95	-0.13 x + 88.24	-0.34 x + 123.47	-0.240 x + 107.53
BMI	R^2	0.018	0.012	0.001	0.004
		-0.38 x + 75.67	-0.37 x + 74.91	-0.11 x + 66.00	-0.22 x + 70.85
		Internal-External Rotation			
		Women		**Men**	
		Right	**Left**	**Right**	**Left**
Age	R^2	0.001	0.051	0.001	0.001
		0.01 x + 22.66	0.011 x + 18.16	0.01 x + 20.85	0.03 x + 18.25
Body weight	R^2	0.054	0.010	0.002	0.023
		0.14 x + 14.69	0.08 x + 17.05	-0.02 x +22.79	-0.07 x + 24.33
Standing height	R^2	0.029	0.001	0.001	0.006
		-0.14 x + 45.75	0.04 x + 15.21	-0.01 x + 22.85	-0.05 x + 28.9
BMI	R^2	0.066	0.008	0.001	0.02
		0.49 x + 12.01	0.22 x + 17.20	-0.06 x + 22.61	-0.26 x + 25.73

All equations are Y (knee ROM) = a X (age/ anthropometry) + b.
R^2: squared correlation index.
All correlation indexes were not significant ($p > 0.05$).

used as standards. Treadmill walking is becoming more and more disseminated, because an increasing number of people is attending fitness centres during their leisure time. Indoor walking can be performed any time, with any weather, and with more general safety than overground walking, especially in urban environments. Moreover, the treadmill is often used in rehabilitation programs because it allows standard and controlled conditions and it needs small spaces.

Recent studies performed overground at self selected speed analysed the walking timing during stance and swing phase [5], stride length and width, gait speed and cadence [9-11, 24, 25], while in the current study the knee joint ROM was investigated during treadmill walking at standardized speed.

In the present study, during treadmill walking the average flexion-extension ROM of leg relative to the thigh was 65° in men and 68° in women. In women aged 46-60 years, Gok *et al*. [26] found a mean flexion-extension ROM of 55° during overground walking. The 10° difference may be explained by the presence, in the current survey, of younger subjects, even if in the present subjects no relationships between age and knee ROM were found. Accordingly, Owings and Grabiner [8] found significant differences in width step between older (age 73.3 ± 2.3 years) and young adults (age 27.7 ± 3.3 years) during treadmill walking at a comfortable, self-selected velocity.

Differences in stride length and gait cadence are manifest when comparing children to adults, while the knee joint ROM should be constant. Indeed, in 3-7 years old children, Tingley *et al*. [27] found 60° of knee flexion-extension.

Recently, Doriot and Wang [28] investigated age and sex differences in upper body joints ROM. While in most cases the comparison of principal joint ROM (trunk, neck, shoulder, elbow and wrist) did not show significant sex differences, significant effects of age were found in particular for trunk, neck and shoulder joints. Indeed, different protocols were used: Doriot and Wang [28] required maximum voluntary movements, while in the current study only habitual movements were measured, which seem to be maintained with similar characteristics at least until the 8th decade of life.

The presence of internal-external knee rotation movements coupled with the principal flexion-extension motion (nearly 22°, Table **2**), similar to those found by Favre *et al*. [29] in healthy adults (about 26°, during overground phases), denotes some variability in walking coordination to assure flexibility and adaptability against possible perturbations during the action [30].

In healthy subjects walking on a treadmill in standardized conditions, the variability given (or produced) by gender anatomical differences, like pelvis width, valgus knee in women, weight and stature, produced small differences only in knee flexion-extension ROM (mean difference less than 3°), while in knee internal-external rotation ROM no differences were found. Indeed, also other authors did not find differences between men and women in knee torque (both sagittal and coronal plane) during barefoot overground walking at natural, comfortable speed (speed value not specified; 7), and in stride length [31].

In contrast, in Korean adults walking overground at a self chosen speed, Cho *et al*. [6] found differences in coronal plane knee ROM (on average, women had a 2.6° ± 0.8 larger valgus motion than men during the gait cycle), but no significant differences in the sagittal plane ROM (64.1° ± 4.6 in men, 64.9° ± 4.6 in women).

Indeed, even considering the different experimental conditions (free chosen overground speed versus imposed treadmill speed) between the current investigations and the previous studies [6, 7], knee ROM during walking seems to be largely independent from sex, at least for healthy sedentary adults.

Moreover, the present minimal sex-related discrepancy (approximately 4.5% of the total ROM) may possess no practical or clinical value, and it may be perceptible with difficulty. The power analysis found that the lack of statistical significance was not due to an insufficient number of subjects, or to a too large intra-sex variability. Within sex, the lack of significant relationships between knee ROM and anthropometric characteristics (weight, height, BMI) could indicate that a similar treadmill walking at low speed (1.0 m/sec) occurs in spite of different body features. As previously found for cadence [10] and for stride time variability [25], the current survey confirmed that aging does not seem to macroscopically modify the motor control strategies of knee joint in unperturbed conditions.

The almost perfect symmetry found for both angular motions indicate that the lower limb lateral dominance does not affect the amplitude and the capacity of movements in knee joint, at least for persons with a right-side dominance; similar findings were reported also by Zverev [31] for normalized step length of right and left feet.

Our results, referring to knee ROM treadmill walking with imposed speed condition, are comparable with other gait studies performed overground [6, 26, 27, 29]. Accordingly, in healthy adults knee ROM seems to be similar when performed overground or on a treadmill at a self-chosen speed next to 1.0 m/sec. Therefore, the use of treadmill for gait analysis could assure a controlled and convenient environment for testing. Furthermore, multiple gait cycles can be analysed obtaining results reliable also for overground gait.

CONCLUSION

In conclusion, in healthy sedentary adults, treadmill walking is performed with knee ROMs that are largely independent from age, sex or anthropometry. Only sagittal plane knee ROM was larger in women than in men, but the actual mean difference was less than 3°.

Further investigations should assess the motion of other body joints during treadmill walking, as well as the effect of increasing speed. Additionally, walking at a personal speed should be recorded to find correlations between ROM and anthropometric characteristics (e.g. lower limb length) free from induced speed gait.

Study Limitations

Knee flexion and extension are performed through simultaneous rotations and translations, while the present study used a simplified three-marker system that did not separate the contribution of the two movements. The associated movement (frontal planes) may probably be those most influenced by the limitations imposed by the current simplified thigh-leg model even if the magnitude of the angles during walking is comparable to those reported by other authors [6, 7, 29].

A further limitation is the use of sedentary subjects: in athletes, movements may be performed with different ROMs due to different stride length and strength levels.

Practical Usage and Clinical Implications

The quantitative analysis of knee ROM is currently performed in the clinical practice both for diagnosis and follow-up after orthopedic treatment and rehabilitation [32], and during the evalutation of deficit and limitation due to neurological diseases [33]. Overall, in the flexion-extension range, sex differences in knee joint ROM during walking were limited, and, even when statistically significant, were clinically negligible. Also, anthropometry or age did not influence knee ROM. The current widespread use of treadmills within fitness and sports centres may therefore be performed with the same instruments and protocols independently from age, sex or anthropometric characteristics, at least for a 1 m/s speed.

The current results, similar to those found in other investigations [6, 26, 27, 29], made the present lower-limb model useful for patient evaluation, allowing a simple and fast analysis of knee movements during walking in controlled conditions that may be well replicated in longitudinal assessments.

ACKNOWLEDGEMENTS

The precious statistical assistance of Mr. Bruno Lovecchio, B.Sc., is gratefully acknowledged. The expert secretarial assistance of Ms. Cinzia Lozio is also acknowledged.

Relevance

In healthy sedentary adults, treadmill walking at standardized speed is performed with symmetric knee movements that are independent from age or anthropometry. Flexion-extension range of motion is larger in women than in men, but the difference has limited practical significance. Current data may be useful for treadmill manufacture.

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Received: February 4, 2008 Revised: March 8, 2008 Accepted: March 19, 2008