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Influence of Arm Motion on Spatio-temporal Gait Parameters and on Force Data

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Abstract:*Computational models of walking are not often coherent with experimental design. Although the upper extremities have an active role in human gait, their swing is often neglected or restricted in contrast with the experiments where the subjects are asked to walk freely. The purpose of this study is to assess differences on gait parameters and force data, comparing five arm swing patterns during walking. Motion analysis was performed on six healthy males, using a 10 cameras capture system and two AMTI force plates. Stride time and length, step time and length as well as ground reaction forces and free vertical moment were compared among groups. Results included no statistically difference (p> 0.05) for the gait parameters and the ground reaction forces. However, the main influence of the arm swing was found on the free vertical moment induced by lower limb swing to counterbalance trunk torque. In fact, restraining arms from swinging caused an increase of peak magnitude in the vertical toque between foot and ground. This suggested that although the arms have a little effect on the sagittal and frontal plane, their contribution is relevant in the transversal one. Therefore, an agreement between experiment-modelling is required, especially when upper body inverse dynamic problems are investigated.*
Keywords: *Arm swing, free vertical moment, gait parameters, ground reaction forces, motion analysis.*

I. Introduction

Most studies on human walking are narrow in focus on the kinematics and kinetics of lower limbs. Indeed, in order to simplify the experimental procedure and the data processing, the markerization of the upper limbs is often avoided. Additionally, in musculoskeletal analyses, the upper body is sometimes considered as a single head–arms–torso segment (HAT model) [1-3], even when collected data refer to a walking with normal arm swing [4]. However, to date, it remains unclear if the movement of arms during gait could be neglected in the computational simulations and if the hypothesis of single rigid body for the head-arms and torso is still valid, although an inconsistency with the experimental design exists.

The aim of the present study is to clarify this point, starting by an investigation of the effect of the arm motion on gait parameters, the ground reaction forces (GRFs) and the free vertical moment during walking. These parameters were chosen because they do not rely on a model but can be directly obtained from recorded data. On the other side, GRFs and free moments are the input of a musculoskeletal gait model, which can produce differences in simulation results. We hypothesized that the influence of restraining arm swing would be already seen in gait variables before developing the musculoskeletal models. In particular,since the arms counteract the rotation of the trunk in the opposite direction around the vertical axis [5], we expected that the main influence would be found in the vertical moment between foot and ground and in the medial-lateral ground reaction force. Both these variables in the transversal plane would show lower peaks when the arm motion is reduced.

II. Material and Method

Six healthy males,with ages ranging between 25 and 30years and BMI below 25 kg/m^2, participated in the study. A total of five types of arm motion during gait(Fig. 1)were considered: (1) small arm swing (SAM); (2)normal arm swing (NAM); (3) large arm swing (LAM); (4) bonded arms (BAM); (5) crossed arms (CAM). Subjects were asked to repeat six times each type of gait for a total of 180 runs.

The Vicon Motion Capturing System (Vicon Motion Systems, Inc, Oxford, United Kingdom) was used for the motion analysis. It consists of ten digital cameras at a frame rate of 150 Hz. Synchronously, the ground reaction data were recorded at 900 Hz, using two force plates (AMTI, OR6 Series, MA, USA). Forty-seven reflective markers (12 mm diameter) were placed on anatomical landmarks according to a customized full-body skin marker set.

Figure 1: Investigated walking tasks. (1) walking with a small arm swing (SAM); (2) with a normal arm swing (NAM); (3) with a large arm swing (LAM) (4) with bonded arms (BAM); (5) with crossed arms (CAM).

InVicon Nexus software, each marker was labelled and all temporary gaps in trajectories were filled using a spline interpolating function. Data were then filteredwith a second-order, zero-phase, low-pass Butterworth filter. A cut-off frequency of 7 Hz for trajectories and 23 Hz for forces and moments were chosen.

III. Data Analysis

The gait events, Heel-Strike (HS) and Toe-Off (TO), were identified from thevertical component of the ground reaction, using a threshold of 10 N for HS and 5 N for TO, respectively [6-9]. When HS and TO were outside the two force platforms, the foot velocity algorithm approach was pursued [10]. The gait parameters (step and stride time, stance and swing time andstep and stride length) were then yielded from the values of HS and TO (Fig. 2). The spatial ones were scaled by each subject's height (BH), whereas the temporal gait variables were normalized by the square of the ratio of each subject's height to gravitational acceleration ($t_0=\sqrt{(BH/g)}$)[11].Because of the small sample size, normal distribution cannot be ensured. As a consequence, the non-parametric Kruskal–Wallis's test was used to compare differences in gait parameters among the five dynamic tasks with the significance level set at 0.05. If a significance was found, a post-hoc analysis was performed using a Bonferroni correction. All the statistical analyses were carriedout using R Project.

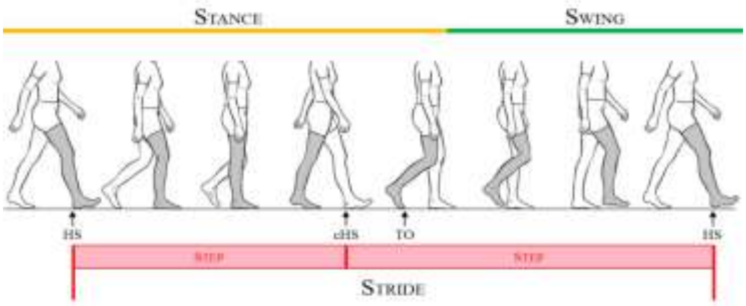

Figure 2: Subdivision of gait cycle on the basis of foot contact data (HS, heel strike; cHS, contralateral heel strike; TO, toe off).

Each AMTI force platform produces six signals, the force componentsF_x (medio-lateral force), F_y (anterior-posterior force), and F_z (vertical force), and the momentsM_x, M_y, and M_z. Since the origin of the local coordinate systemon each force plate (O) is centeredat a distance (d) below its surface, the reaction couples exerted by the foot on the ground and applied on the center of pressure (COP) are given by:

$$\vec{T} = \vec{M} - \vec{k} \wedge \vec{F} \qquad (1)$$

where$\vec{F}$and$\vec{M}$ are the forces and the moments about the origin of the local coordinate system$O$ and $\vec{k}$ the vector joining O to the COP. Usually, only the couple about the vertical axis, referred as the free vertical moment, T_z, is considered.

The ground reaction forces and the free vertical moment, recorded during the stance phase of the gait, were scaled by percentage of body weight (BW)and bythe percent product of bodyweight and height (BWH), respectively.Data were interpolatedto 100% of the stance phase. For each condition, the time series wereaveraged. The standard deviations were calculated within each subject and each condition and then averaged across all subjects.

For the force components, the magnitudes of peaks were compared and the non-parametric Kruskal–Wallis's test was performed.Pearson correlation coefficient (r), averaged across subjects, was used to assess temporal similarity between T_z waveformsfor each pair of tasks.

IV. Results

The median values of gait parameters across all subjects and range for each gait type are reported in figure 3. The normalized stride length and time are about 0.8 and 2.65 respectively, with very small differences in the five types of gait. Similar observations can be extended to step parameters, that are reported both for dominant and non-dominant limb. The differences between the limb are minima, with the dominant side showing higher values. It can be further observed that step parameters are equal to the half of the stride ones.

However, as far as this time and length parameters is concerned, no statistically difference (p> 0.05) was found during walking, changing the arm motion in amplitude.

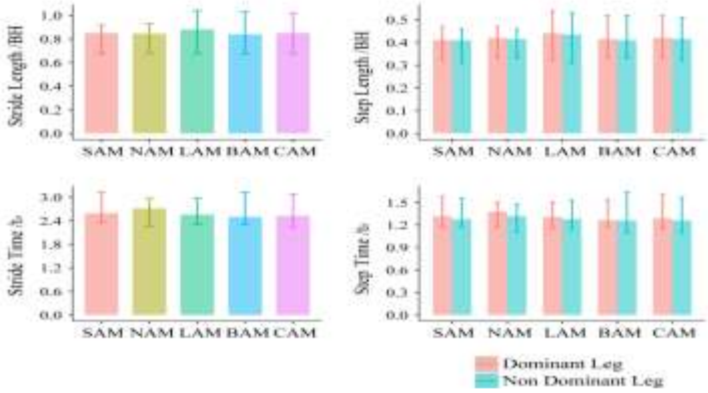

Figure 3: Normalized stride length and stride time (left) and normalized step length and step time (right) for each arm condition (small arm motion, SAM; normal arm motion, NAM; large arm motion, LAM; bonded arm motion, BAM; crossed arm motion, CAM). Error bars represent the range.

Figure 4 shows time trends of the vertical, anterior-posterior and medial-lateral components of the ground reaction forces during the stance period, averaged across participants, for the five types of gait. Also in this case, dominant and non-dominant limb are analysed separately. The medial lateral force component appears to show the major differences for the five types of gait, while for the anterior-posterior and axial components curves of different arm motion are almost overlapped. However, in terms of magnitude, the former is the smallest (> 8% BW) while the anterior posterior reaches 20% BW and the normal component even can be up to 120% BW.

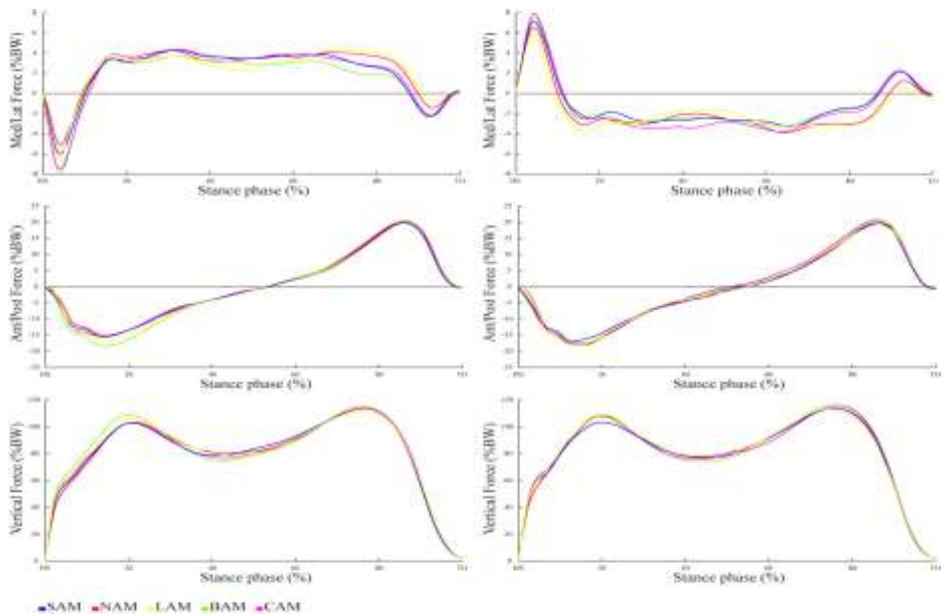

Figure 4: Averaged ground reaction forces for each walking task. The medial-lateral, anterior-posterior and vertical components are reported for non-dominant (left) and dominant limb (right).

Table 1 contains the mean (±SD) values of force components at some peculiar instant of the stance phase, shown in Figure 4. Also in this table a distinction is made between dominant and non-dominant limb.Peaks component are not statistically significantly different from each other at the 0.05 level.

Table 1: Mean and standard deviation (SD). GRF peaks for walking with a small arm motion (SAM), a normal arm motion (NAM), a large arm motion (LAM), with bonded arms (BAM), with arms held across the chest (CAM).

GRF peaks		Arm Condition				
		SAM	NAM	LAM	BAM	CAM
Medial-lateral component						
1st peak (%BW)						
	Non-Dominant	-5.99 (0.87)	-5.13 (1.03)	-6.58 (1.03)	-7.80 (1.37)	-7.52 (0.86)
	Dominant	7.11 (1.08)	6.57 (1.06)	6.03 (0.84)	7.54 (1.42)	7.88 (0.87)
Anterior-posterior component						
1st peak (%BW)						
	Non-Dominant	-15.47 (2.78)	-15.16 (1.57)	-14.28 (1.30)	-18.35 (1.93)	-13.87 (1.04)
	Dominant	-16.98 (1.62)	-17.78 (1.25)	-18.13 (1.48)	-18.23 (2.37)	-17.67 (1.51)
2nd peak (%BW)						
	Non-Dominant	19.77 (0.92)	19.95 (0.91)	20.79 (1.95)	20.07 (0.65)	20.35 (1.03)
	Dominant	19.79 (0.84)	19.77 (1.39)	19.02 (0.94)	21.00 (1.15)	20.46 (1.16)
Vertical component						
1st peak (%BW)						
	Non-Dominant	102.84 (5.34)	103.15 (3.27)	106.06 (3.34)	108.58 (3.34)	102.70 (6.16)
	Dominant	103.33 (4.46)	107.65 (3.94)	107.07 (2.98)	108.95 (3.95)	107.64 (3.33)
2nd peak (%BW)						
	Non-Dominant	111.68 (1.45)	113.51 (2.78)	111.72 (1.93)	115.26 (2.31)	113.98 (3.09)
	Dominant	113.53 (2.29)	113.58 (2.16)	113.08 (2.21)	116.90 (2.63)	115.31 (2.06)
Valley (%BW)						
	Non-Dominant	78.39 (3.43)	80.16 (3.18)	78.61 (2.41)	74.66 (2.20)	76.52 (2.88)
	Dominant	77.69 (2.25)	76.74 (3.10)	78.36 (2.38)	73.52 (3.18)	75.71 (2.35)

Figure 5 depicts the free vertical moment both for dominant and non-dominant stance. It must be observed that for all subjects the dominant side was the right, thus the differences between the two limbs also show an opposite sign of the couple. Rather interestingly, the magnitude of this moment increases with the type of arm motion condition from LAM, to NAM, SAM, BAM up to CAM. Thus, the arm motion seems to reduce the internal external moment at the ground interface, the lower the motion the higher the moment.

Assessment of *r* values between pairs of T_z curves indicates that the patterns for SAM, BAM and CAM are more similar in temporal characteristics (r = 0.88-0.95) than the trends for NAM and LAM with r = 0.67. As regards walking with NAM compared to walking with SAM, BAM and CAM, Pearson correlation coefficient is about 0.76. When the arm elevation is more pronounced (LAM), r decreases and ranges between 0.57 and 0.67. The lowest correlation is recorded for the pair LAM and SAM.

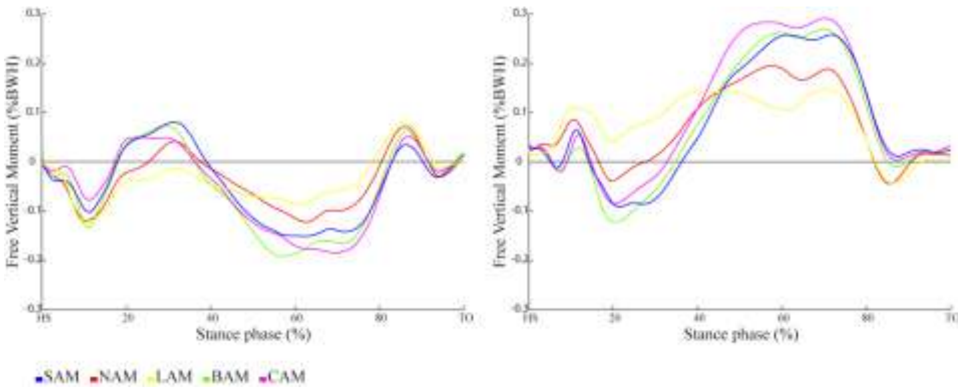

Figure 5: Averaged free vertical moment for each walking task and for non-dominant (left) and dominant stance (right).

V. Conclusion

The purpose of this study was to assess whether differences exist in gait parameters, ground reaction forces and the free vertical moment during walking when modifying the amplitude and position of arms.

Results showed that the spatiotemporal gait parameters are not significantly affected by the arm motion condition. Also dominant and non-dominant limb do not show noticeable differences. On the other side, in agreement with Umberger et al. [12] and Li et al. [13], differences in magnitude and in trends can be appreciated for the free vertical moment. This suggests that the transversal plane variables are affected by trunk rotation and by the changes of arm-swing amplitude. Therefore, when a musculoskeletal model is used to investigate joint reactions, the role of the arms cannot be disregarded, as frequently done in practice to reduce processing time consumption. In fact, a recent study [14] shows that the spinal axial force, measured with a telemeterised vertebral body replacement during arm elevation in standing position, considerably increases due to the flexion moment created by arms.Future investigations will be focused in this direction and will consist in the development of a model for each subject and in the simulation of the five tasks for joint reaction estimation.

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