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How toe-out foot positioning influences body-dynamics during a sit-to-stand task

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ABSTRACT

Background: Toe-out foot positioning is increasingly analyzed as a compensatory body-mechanical strategy to reduce pain and joint constraints in people with degenerative joint disease during gait. However, its influence during functional tasks, such as sit-to-stand, has not been reported.

Research question: How uni- and bilateral toe-out foot positioning influence body-dynamics during a STS task?

Methods: The study was conducted on 15 healthy participants. Seven feet conditions were tested: neutral (N); right toe-out angle of 10° (U10), 20° (U20), and 30° (U30); bilateral toe-out angle of 10° (B10), 20° (B20), and 30° (B30). Execution time, trunk kinematic, vertical ground reaction force ratio as well as maximal knee and hip joint moments were analyzed and compared.

Results: A significant difference was found across conditions in the STS execution time ($p = 0.036$) showing a main effect on temporal parameters using both uni- and bilateral toe-out foot positioning. A significant difference between conditions was also obtained for the vertical force ratio ($p = 0.018$) and the maximal knee flexion moment ($p = 0.008$). *Post-hoc* tests demonstrated a significant difference on force ratio and on knee flexion moment only while using a more pronounced unilateral toe-out foot positioning.

Significance: The influence of toe-out foot positioning on body-dynamics during STS supports the idea of an alteration of body-mechanical strategy, as reported in literature gait studies. The results could have an impact on the management of patients using these strategies in order to reduce the onset of secondary joint diseases such as osteoarthritis.

1. Introduction

Decline of functional capacities in individuals affected by degenerative joint diseases compromise their autonomy and their independence in daily activities [1]. Rikli and Jones have defined functional capacity as the physiological capability to perform daily activities (e.g., locomotion, sit-to-stand [STS]) safely and independently without excessive fatigue [2]. Additional factors, such as pain, biomechanical factors, and disabilities related to joint diseases could also be associated with a decline in body function.

It is documented that human beings consciously or subconsciously develop body-mechanical strategies to cope with pain, and thus improve their capacities to realize tasks of daily living. These strategies could even delay the timing of the intervention by reducing joint symptoms. For example, Hunt et al. demonstrated that people with severe knee OA modified their walking mechanics in comparison to individuals with less severe OA, and to those without symptoms [3]. They showed that the lateral trunk lean is used as a compensatory response to OA disease. As reported, an increase of the trunk lean on the affected side will lateralize the ground reaction force vector, which will decrease the external knee and hip adduction moments [3]. Another body-mechanical strategy adopted by people with knee OA is the increase of the toe-out angle. As reported for the trunk lean, the use of a more pronounced toe-out angle lateralizes the ground reaction force vector and reduces the knee adduction moment [4]. However, even though body-mechanical strategies are used to manage symptoms and increase function, the long-term influence of these strategies is still not well understood [5]. It is unclear on whether they could be used as a gait retraining protocol to reduce pain, or whether they inflict long-term damage.

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In recent studies, gait-retraining have been explored in knee OA populations [4,6]. In the study conducted by Hunt et al. [4], the authors proposed to examine the feasibility of a toe-out gait program in individuals with medial tibiofemoral knee OA. Their goal was to evaluate changes in clinical and biomechanical outcomes after a ten-week retraining. They observed a reduction in the knee adduction moment, and a significant improvement in clinical outcomes. Their study was in agreement with the study led by Shull et al. [6] who demonstrated that gait retraining (i.e., alteration of toe-out angle and/or trunk sway angle) could decrease knee adduction moments and symptoms associated with the disease and improve function.

Although compensatory strategies are increasingly analyzed during gait, these strategies have rarely been reported in the literature during functional tasks that are more challenging [7,8]. In a previous study, a similar compensatory behavior was reported as that encountered during gait for performing a STS task [7]. The authors reported a significant increase of the trunk lean in individuals with knee OA toward their affected knee compared to healthy elderly. However, the influence of toe-out foot positioning was not reported [7]. In another study, Guo et al. investigated the influence of the toe-out angle on the knee adduction moment during stair climbing [8]. Increasing the toe-out angle significantly increased the peak of the first knee adduction moment and significantly reduced the second peak. Given that the toe-out foot positioning (unilateral or bilateral) could significantly influence joint kinetics and disease symptoms during gait [4], and that there is a gap of knowledge of its influence on functional tasks, it would be interesting to investigate more extensively its influence during STS movements.

Modification in movement patterns associated with the completion of a STS is recognized in elderly and individuals with degenerative joint disease [7,9–14]. Increases of trunk movement as well as a decrease in the movement speed, are also recognized as body-mechanical strategies used to facilitate the realization of this task [15]. These modifications are generally used to decrease pain, achieve a better postural stability both leading to an increase of functional capacities. Many determinants related to the STS performance have been identified in the literature [16]. Janssen et al. proposed three main categories: chair-related determinants (height, armrest, type, backrest), subject-related determinants (age, disease, muscle force, footwear), and strategy-related determinants (speed, foot position, trunk position, arm use, terminal constraint, arm movement, light, fixed joints, knee position, attention, and training) [16]. This study concluded that the height of the chair, the use of armrests, and the foot positioning, have a major impact on STS performance, and should always be standardized when evaluated. Foot positioning during STS has been extensively studied [15,17–30]. Authors report—among other things—that foot-forward position increases the amplitude and the speed of the trunk flexion [28]. A foot-forward position also increases the hip joint moment in the sagittal plane [20]. In contrast, the foot-back position will decrease the time to realize the task, the contribution of the hip joint moment, and its velocity in the sagittal plane. The foot-back position is also recognized as important in decreasing the hip joint moment and increasing stability during an STS movement [20]. However, no studies had demonstrated the influence of frontal foot positioning during a STS.

The aim of this study was to determine the influence of uni- and bilateral toe-out foot positioning on body-dynamics during a STS task. We first hypothesize that an increase of time execution while using an increased toe-out foot positioning (unilateral or bilateral) should be observed. Secondly, we hypothesize that an asymmetry for lower body kinetics and for trunk kinematics should be generally observed while using a more pronounced unilateral toe-out foot positioning.

2. Methods

The study was conducted on 15 healthy participants (6 males and 9 females). All participants had no pain or recent history of surgery or disorders of the musculoskeletal system at the lower limbs. All participants reported to be right-handed. Their mean age, mass, height, and body mass index (BMI), were 23 (SD 4) years, 67.4 (SD 10.9) kg, 1.71 (SD 0.10) m, and 22.93 (SD 2.4) kg/m^2, respectively.

Participants signed an informed consent form before their participation in the study protocol. The study was approved by the ethical committee of the *Institut de réadaptation en déficience physique de Québec* (IRDPQ-CIUSSSCN) (project #2016 − 499).

2.1. STS assessment

The participants wore neutral shoes to avoid biases, as increasing or decreasing joint loading [31]. They sat on a backless and armless instrumented chair, with the chair height set to place both knees at 90° with both tibias aligned vertically with respect to the floor, and with feet placed at shoulder width. The knee angles were confirmed with a long-arm goniometer prior to each condition. Following a practice trial, the participants were asked to stand up from the chair at their self-selected pace, and were instructed to keep both arms crossed on their chest. Seven different feet positions were tested: neutral (N), right toe-out angle of 10° (U10), of 20° (U20), and of 30° (U30), and bilateral toe-out angle of 10° (B10), of 20° (B20), and of 30° (B30). A right toe-out angle condition was preferred to left considering that all participants reported to be right-handed. The different conditions were implemented in a randomized way to avoid bias. Each participant completed four trials per condition. Constant foot placement was ensured using a plastic film (apposed on each force plate) with set angles for each condition marked by a line (Fig. 1A and B). The evaluator positioned the feet of the participants for each condition (allowing a resting period between conditions), and the participants were instructed not to move their feet between trials. The first three well-executed trials (i.e., where the participant fulfilled all instructions, and where good feet position and visibility of all markers was achieved) per condition were used for data analyses.

2.2. Instrumentation and data processing

A three-dimensional motion analysis system including nine cameras (VICON, Denver, USA) was used to capture kinematics at the trunk and

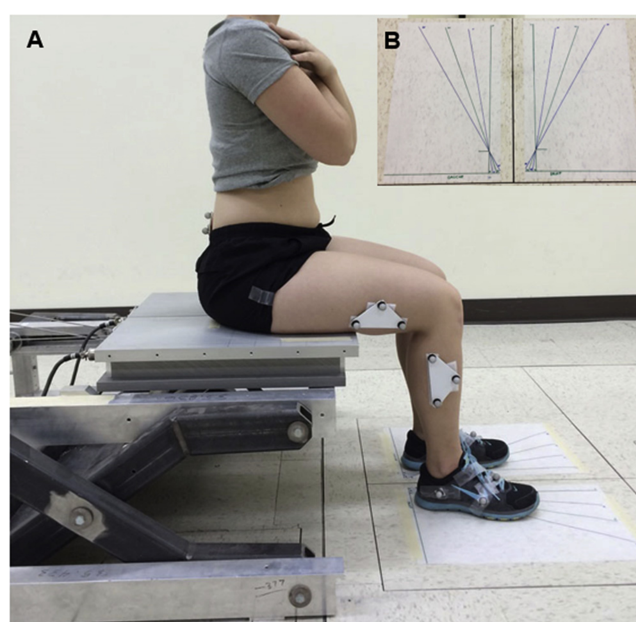

Fig. 1. Instrumented chair used to capture the force under each thigh using two force plates (AMTI-BP250 × 500-1K-2931, Watertown, USA). Fig. 1A illustrates the STS set-up and 1B the plastic film apposed on each force plate to set angles for each condition.

lower limb levels during a STS task. Eight clusters of noncollinear reflective markers were affixed to the lateral side of feet, shanks and thighs, at pelvis (L5) and trunk (C7), respectively. Eighteen additional reflective markers were used for the calibration trial, and were fixed bilaterally on the following anatomic landmarks: fifth metatarsal, medial and lateral malleoli, medial and lateral femoral condyles, left and right iliac crests, left and right anterior superior iliac spines, and heel and head of second metatarsal. All the raw coordinate data were sampled at 100 Hz and further smoothed using a zero-lag, second-order Butterworth filter, with a cut-off frequency of 6 Hz. Joint kinematic data were subsequently calculated using custom software based on models from equations used in the Kingait3 software package (Mishac, Inc, Waterloo, Ontario) [32], which utilizes the same approach as previously published methods [33].

An instrumented chair was used to capture the force under each thigh using two force plates (AMTI-BP250 × 500-1K-2931, Watertown, USA). The chair was designed to be adjustable in height (ranging from 39 cm to 72 cm) and has no armrests (Fig. 1A).

Two other force plates (FP4060-NC, Bertec Columbus, U.S.A.) embedded in the floor were used to measure the ground reaction forces under each leg. All force plate data were sampled at 1000 Hz and synchronized with motion data. Kinetic data were filtered offline using a zero-lag, second-order order Butterworth filter, with a cut-off frequency of 50 Hz. Newton–Euler inverse dynamics equations were then used to estimate three-dimensional reaction forces at joint centers and net muscle moments of force for the lower limb joints. The joint moments were normalized against body mass.

The complete movement of the STS task was analyzed in three phases (Fig. 2). The beginning (T0) and the end (T3) of the task were determined using the angular velocity of the thoracic segment. T0 was determined when the anterior posterior angular velocity increased above zero. Correspondingly, T3 was determined when it returned to zero [10]. Two other instants were identified: the seat-off (T1) and the peak value of the vertical floor reaction forces (T2). The seat-off corresponds to the instant at which the seat vertical forces decrease to less than 6 N. The peak value of the floor reaction forces was identified using the maximum value of the summation of both vertical ground reaction forces.

Kinematic, kinetic, and temporal parameters were analyzed. The average time to complete the STS task, and the time intervals between T0–T1, T1–T2 and T2–T3, were calculated and compared between conditions. The ratio of the maximal vertical ground reaction forces (GRFvmax) for the lower limbs at T2 was then calculated. This ratio corresponded to the GRFvmax of the right side divided by the GRFvmax of the left side. The right knee adduction moment and the right knee and hip external flexion/extension moments were obtained from inverse dynamics. The peak values for each variable were extracted from the complete STS movement. Finally, the maximum flexion and inclination of the trunk (i.e., angle relative to the global reference frame) during the complete STS movement were also identified.

2.3. Statistical analyses

The average values for the feet positions and for all the described variables were obtained by averaging the discrete values across the three selected trials. All the computations were performed using custom Software and MATLAB R2014a (Mathworks, USA).

The assumption of normally distributed data was verified using the Kolmogorov–Smirnov test, and was confirmed for all variables. Consequently, differences between the seven-foot conditions (N, U10, U20, U30, B10, B20, B30) were compared using one-way repeated measures ANOVA. When the Mauchly's test detected heterogeneity of variance for a repeated measures effect, the Huynh-Feldt correction was applied; otherwise sphericity was assumed. Post-*hoc* pairwise comparisons were then calculated with the EMMEANS COMPARE option of the SPSS' GLM procedure. A significant difference was set at a p level $<$ 0.05.

3. Results

As hypothesized, the results show a significant difference across conditions for the STS execution time ($p = 0.039$; $\eta p2 = 0.143$).

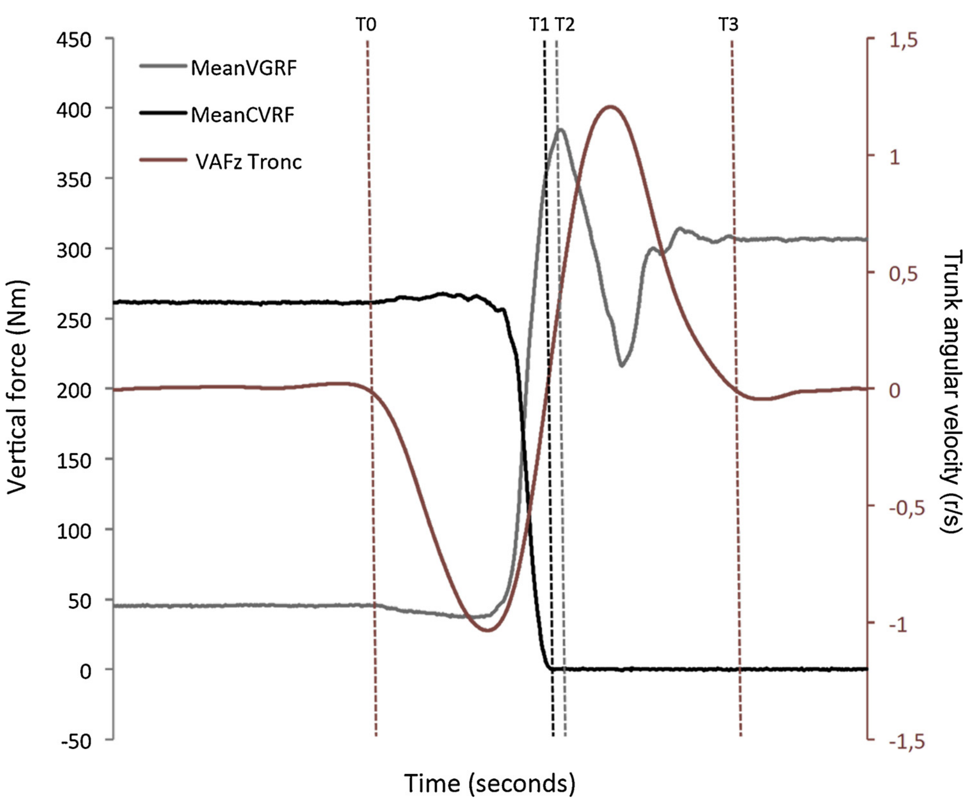

Fig. 2. Illustration of the STS phases determination. T0 (beginning) was determined when the angular velocity of the trunk segment (VAFz) increased above zero and T3 (end) when it returned to zero. The seat-off (T1), instant at which the seat vertical forces (CVRF) decrease to less than 6 N, and the peak value of the vertical ground reaction forces (VGRF) (T2).

Table 1
Mean and standard deviation of time parameters, vertical GRF ratio, joint moments and trunk angles variables during the sit-to-stand (STS) task across conditions (Neutral [N]; Right unilateral toe-out angle of 10° [U10], 20° [U20], 30° [U30]; bilateral toe-out angle of 10° [B10], 20° [B20], 30° [B30]).

	N	△U10	△U20	△U30	△B10	△B20	△B30
COMPLETION TIME							
STS task (sec) *	2.29 (0.32)	2.27 (0.30)	2.35 (0.34)	2.40 (0.31)	2.32 (0.35)	2.37 (0.35)	2.48 (0.46)
T0-T1 phase (sec)	0.97 (0.14)	0.96 (0.14)	0.95 (0.16)	1.00 (0.16)	1.01 (0.16)	0.99 (0.17)	1.01 (0.15)
T1-T2 phase (sec)	0.04 (004)	0.04 (003)	0.04 (003)	0.03 (002)	0.05 (004)	0.04 (003)	0.04 (004)
T2-T3 phase (sec) *	1.29 (0.26)	1.27 (0.27)	1.36 (0.26)	1.37 (0.28)	1.26 (0.25)	1.35 (0.24)	1.44 (0.40)
GRFvmax ratio *	1.05 (0.10)	1.08 (0.14)	1.13 (0.16)	1.04 (0.12)	1.07 (0.09)	1.06 (0.11)	1.05 (0.10)
MOMENTS							
Knee Flex peak * (Nm/kg)	0.87 (0.21)	0.89 (0.22)	0.86 (0.23)	0.80 (0.17)	0.89 (0.22)	0.87 (0.21)	0.86 (0.18)
Hip Flex peak (Nm/kg)	1.03 (0.16)	1.04 (0.15)	1.07 (0.16)	1.06 (0.18)	1.03 (0.16)	1.01 (0.13)	1.00 (0.15)
Knee Add peak (Nm/kg)	0.14 (0.10)	0.14 (0.10)	0.14 (0.10)	0.12 (0.09)	0.13 (0.10)	0.12 (0.08)	0.13 (0.09)
ANGLES							
Max Trunk Flexion (°)	42 (9)	41 (10)	42 (11)	42 (10)	42 (9)	41 (11)	42 (9)
Max Trunk lean (°)	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)

Note. Variables showing significant differences across conditions are indicated with an *.

Indeed, results demonstrate an increase in the execution time with an increase of the toe-out angle. *Post-hoc* tests demonstrate a significant increase between the N and B30 conditions (2.29 s vs. 2.48 s; $p = 0.041$), between U10 and U30 conditions (2.27s vs. 2.40s; $p = 0.046$), between U10 and B20 conditions (2.27s vs. 2.37s; $p = 0.049$) and between U10 and B30 conditions (2.27s vs. 2.48s; $p = 0.015$) (Table 1). No significant differences were observed between time intervals T0–T1 ($p = 0.313$; ηp2 = 0.080) and T1–T2 ($p = 0.769$; ηp2 = 0.030). However, significant differences were observed between conditions for the time interval T2–T3 ($p = 0.046$; ηp2 = 0.139). The *post-hoc* tests revealed a significant difference between N and B30 conditions (1.29 s vs. 1.44 s; $p = 0.034$) and between B10 and B30 conditions (1.26s vs. 1.44s; $p = 0.030$).

For the vertical ground reaction force ratio, a significant difference between conditions was also observed ($p = 0.018$; ηp2 = 0.183). Indeed, we observed an increase in the force ratio between N, U10, and U20 conditions. *Post-hoc* tests reveal a significant increase between the N and U20 conditions (1.05 vs. 1.13; $p = 0.018$), and a significant decrease between U20 and U30 (1.13 vs. 1.04; $p = 0.008$), U20 and B20 (1.13 vs. 1.06; $p = 0.001$) and, U20 and B30 (1.13 vs. 1.05; $p = 0.003$) (Table 1).

For the maximum external flexion moment at knee, we observed a significant difference between conditions ($p = 0.008$; ηp2 = 0.182). *Post-hoc* tests demonstrate a significant decrease between N and U30 (0.87 Nm/kg vs. 0.80 Nm/kg; $p = 0.044$) and between U10 and U30 (0.89 Nm/kg vs. 0.80 Nm/kg; $p = 0.009$). Significant differences were also obtained between U30 and B10 (0.80 Nm/kg vs. 0.89 Nm/kg; $p = 0.007$), U30 and B20 (0.80 Nm/kg vs. 0.89 Nm/kg; $p = 0.022$) and U30 and B30 (0.80 Nm/kg vs. 0.86 Nm/kg; $p = 0.016$) (Table 1). The opposite behavior was observed at the hip level. However, no significant differences were noted between conditions ($p = 0.255$; ηp2 = 0.086). No significant difference was observed for the maximum adduction knee moment between time intervals T2–T3 ($p = 0.445$; ηp2 = 0.060).

Lastly, no significant differences were observed between conditions for the maximum trunk flexion ($p = 0.973$; ηp2 = 0.015) and maximum trunk lean angles ($p = 0.687$; ηp2 = 0.045) (Table 1).

4. Discussion

The purpose of this study was to investigate the modification of body-dynamics (i.e., movement patterns and joint moments) according to seven toe-out foot positioning conditions during STS. To the best of our knowledge, this study is the first to characterize kinematic and kinetic parameters associated with toe-out foot positioning during this task. The action of rising from a chair is a functional task that challenges the lower body joints as well as the body equilibrium [34,35].

This study demonstrated that the time to perform the STS, the vertical GRF ratio, and the knee joint flexion moment were the parameters most affected by a toe-out foot positioning. Indeed, even if the time to realize STS remained quite small (ranging from 2.27 to 2.48 s), it increased significantly between conditions with larger foot angles. The largest gap was an increase of 9% (0.21 s) between the U10 and B30 conditions. This suggests that the time to reach body-equilibrium increases with both unilateral and bilateral toe-out foot positioning. Moreover, if we analyzed the variation of the time for each subphase (i.e., T0–T1, T1–T2, T2–T3) and all conditions in detail, the rising phase (T2–T3) (i.e., the phase requiring the greatest force and muscle capacity) is the one principally affected by a toe-out foot positioning. We can hypothesize that the misalignment of lower limbs may require a modification of muscles' recruitment and delay this subphase. In addition, it is assumed that an increase of time for the rising phase would be even more accentuated in individuals with balance disorders or musculoskeletal diseases.

Previous studies have shown a similar time for performing STS tasks in able-bodied individuals and pathological populations [7,29,30]. For example, Lecours et al., reported an average STS time of 2.11 ± 0.39 s for 15 healthy subjects using a self-selected foot condition [29]. However, the times required to complete each subphase have never been reported.

We also observed an alteration in the vertical force ratio between foot placement conditions. As hypothesized, the asymmetrical ratio increased while moving from a neutral foot position (N: 1.05), to a unilateral foot placed at 10° (U10: 1.08) and at 20° (U20: 1.13). Surprisingly, at U30, a ratio value almost equal to the one calculated at the neutral position was obtained (1.04). This suggests that individuals shifted their weight to the contralateral side to keep their equilibrium. A significant decrease of the maximal external knee flexion moment (occurring between T1-T2) was also observed at the U30 foot condition, which supports the unilateral weight shift hypothesis. This hypothesis is strengthened considering that the STS time decreases mostly during T2-T3.

As this study was only conducted on healthy young individuals, we can hypothesize that the elderly population with/without joint pain would present different outcomes in terms of movement velocity and joint amplitude. These outcomes would invariably alter the lower body joint moments. However, although our results cannot be generalized for the elderly, or for people affected by musculoskeletal diseases, we believe that they provide new insights on the influence of toe-out foot positioning during an STS task.

This study is associated with a main limitation that ought to be considered when interpreting the results. Indeed, the research participants were instructed to keep both arms crossed on their chest during the realization of the task. As reported in a study conducted by Carr et al. [36], there is a dynamic relationship between upper and lower limbs during a STS task. Their results demonstrated both temporal association between the onsets of shoulder flexion and lower limb extension and the influence of arm movement on force production in the lower limbs. It suggests that the arms play a key role in the propulsion of the body. Therefore, the use of preferred arm strategies (arm movement, armrest support) instead of restricted one would have likely modified the kinematic and kinetic results. However, this methodological choice was made because we wanted to quantify the influence of toe-out foot positioning, without any other confounding variables. Another limitation could be that the STS task time was not controlled between conditions and could have potentially influenced the kinetics comparisons. However, we preferred to use the STS task time as a performance variable, instead of controlling it and induci unnatural movements.

5. Conclusions

This study is the first to have investigated the influence of toe-out foot positioning on kinematics and kinetics during a STS task. The understanding of how toe-out foot positioning impacts on body dynamics during STS supports the idea of an alteration of body-mechanical strategies. Our results suggest an influence of toe-out foot positioning mainly on temporal parameters, GRF ratio and knee flexion moment. These results would also help define experimental protocols according to foot positioning, and its impact on body-dynamics as well as improve patients' management to decrease the risk to develop secondary joint disease.

Conflicts of interest

None.

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