CLINICAL BIOMECHANICS – BIOMECHANICAL DEMANDS DIFFERENTIATE TRANSITIONING *vs.* CONTINUOUS ASCENT GAIT IN OLDER WOMEN

Lisa Alcock [1,2], Thomas D. O'Brien [3,4], & Natalie Vanicek [2,5]

[1] Institute of Neuroscience, Newcastle University Institute for Ageing, Newcastle University, UK

[2] Department of Sport, Health and Exercise Science, University of Hull, UK

[3] Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, UK

[4] School of Sport, Health and Exercise Science, Bangor University, UK

[5] Discipline of Exercise and Sport Science, Faculty of Health Sciences, University of Sydney, AUSTRALIA

ABSTRACT

Background- The mechanics of stair ascent have been shown to change with age, but little is known about the differing functional demands of transitioning and continuous ascent. Equally, there is a lack of work investigating the important and risky transition from level gait to ascent, and the strategies older adults adopt to achieve these demanding tasks have not been investigated.

Methods- This study compared the biomechanics of a 2-step transitional (floor-to-step2) and continuous ascent cycle (step1-to-step3) and investigated the role of limb preference in relation to dynamometer-derived knee strength during the transition linking level and ascent gait. A biomechanical analysis of 36 women (60-83 years) ascending a 3-step custom-built staircase was conducted.

Findings- The 2-step transitioning cycle was completed quicker, with larger joint range of motion, increased ground reaction forces, larger knee flexor and dorsiflexor moments and ankle powers ($p \leq 0.05$), but reduced peak hip and knee flexion, smaller hip extensor moments and hip and knee powers compared to continuous ascent. During the transition, 44% of participants demonstrated a consistent limb preference. In these cases large between-limb knee extensor strength differences existed (13.8%) and >71% of these participants utilised the stronger limb to execute the 2-step transitional cycle.

Interpretation- The preferential stronger-limb 2-step transitioning strategy conflicts with previous recommendations of leading with the stronger limb for very frail/asymmetric populations during ascent. Instead, our findings suggest that most healthy older women with a large between-limb strength difference utilise the stronger limb to achieve the high levels of propulsion required to redirect momentum during the 2-step transition from gait into ascent. The biomechanical demands observed during ascent, in relation to limb strength, can inform exercise programmes by targeting specific muscle groups helping older adults improve or maintain general functioning.

INTRODUCTION

Stair ascent (STA) is a complex task placing greater demands on the lower limbs with larger joint range of motion (ROM) and joint kinetics compared with level gait (Andriacchi et al., 1980). Substantial postural control is required, while primarily concentric muscular contractions displace the centre of mass horizontally and vertically (McFadyen and Winter, 1988). The heightened demands of STA are amplified further in conjunction with diminishing musculoskeletal capacity during older age (Faulkner et al., 2007; Kang and Dingwell, 2008). Consequently, STA presents a considerable falls risk for older adults (Wyatt et al., 1999) who may adopt altered movement patterns during this challenging task (Hamel and Cavanagh, 2004).

Age-related differences in STA mechanics such as reduced locomotor speeds and increased double-limb support (Benedetti et al., 2007; Stacoff et al., 2005) may be indicative of efforts aimed at improving locomotor safety and stability. Equally, these changes may compensate for declining musculoskeletal function, evidenced by reduced initial peak vertical and anterior-posterior forces, and increased vertical forces in mid-stance in older adults (Bertucco and Cesari, 2009; Hamel et al., 2005). In response to diminishing strength, older adults displace the mechanical demands proximally, and rely on the musculature of the knee rather than ankle to generate the required propulsion during continuous STA (Reeves et al., 2009). Although some of the changes allow older adults to meet the high demands of STA, these adjustments may inadvertently contribute to an increased falls risk.

When approaching the staircase, the lower limbs conform to a typical gait pattern. As STA is initiated, and using a reciprocal stepping pattern, a 1-step gait cycle between the ground and the first step is completed (by what is sometimes referred to as the leading limb). This is followed by a 2-step gait cycle between the ground and the second step (by what is sometimes referred to as the trailing limb), which completes the transition between level gait and STA (see Figure 1). Successive, continuous 2-step STA gait cycles, which are initiated and terminated on the staircase, are then performed until the top of the staircase is reached. Finally, at the top of the staircase a 1-step gait cycle completes the final transition between the staircase and first floor level.

The mechanics of continuous STA have frequently been described (McFadyen and Winter, 1988; Nadeau et al., 2003; Novak and Brouwer, 2011; Reeves et al., 2009; Wilken et al., 2011). In comparison, the biomechanical requirements of the transitioning phase between gait and STA have received less attention. This is an important aspect of stair locomotion to consider given that a Locomotor Risk Index has suggested that the 1-step transition presents an increased falls risk compared to level gait and continuous STA (that study did not consider the 2-step-transition) (Sheehan and Gottschall, 2012). Previous work has examined the 1-step-transition (Benedetti et al., 2007), but few have compared the different 2-step STA cycles (transitioning *vs.* continuous) and limited evidence suggests that the 2-step transitioning cycle is completed significantly quicker with considerably larger external knee moments compared to 2-step continuous STA gait (Andriacchi et al., 1980; Lee and Chou, 2007). However, much remains unknown and further biomechanical investigations are required.

Despite covering the same vertical distance, the 2-step cycles (transitioning *vs.* continuous) may be responsible for distinct functional objectives. Understanding the biomechanical demands of the 2-step transitioning cycle may elucidate the mechanics underpinning adequate control when task demands are high and locomotor function is reduced (e.g., such as in an ageing population). This information may be used in the design and implementation of targeted exercise interventions. Current rehabilitation practice supports the use of the stronger limb to complete the 1-step transition into STA when utilising a 'step-to' gait pattern (whereby both limbs contact each step), as might be performed by those with significant muscle weakness (e.g., very elderly) or functional asymmetry (e.g., amputees). However, it is unknown whether older women adopt a similar strategy during the transition into STA. It is possible that older adults may meet the increased mechanical demands of risky situations by selectively leading with the weaker limb, thus allowing the stronger limb to execute the 2-step transitioning cycle which we believe is more challenging than the 1-step transition due to its greater vertical displacement. Such a theory would contradict current practice with other clinical populations, but may reveal the compensatory musculoskeletal strategies older adults make subconsciously in response to changing biomechanical capacities.

Considering the high incidence of falls that occur near either the top or the bottom of the stairs (Jackson and Cohen, 1995; Templer, 1978, 1992), it is surprising that so much remains unknown about the transitioning phases linking level and STA gait. By understanding the biomechanical demands of continuous and transitioning STA, strategies to meet these demands and reduce falls risk may be developed and interventions may be tailored appropriately. This information would be particularly valuable to older women due to a greater incidence of falls amongst women compared to men and the higher falls risk associated with stair locomotion (Blake et al., 1988; Campbell et al., 1989; Gine-Garriga et al., 2009). Older women also exhibit reduced muscle strength compared with men (Hughes et al., 2001), making them more susceptible to instability during challenging tasks like STA. The aim of this study was to quantify the biomechanical differences between the 2-step transitioning and continuous STA cycles in healthy older women. It was hypothesised that the 2-step transitioning cycle would vary mechanically to continuous STA due to the differing functional objectives when transferring the body from level gait (horizontal translation) to STA (combination of horizontal and vertical translations). A second aim of this study was to evaluate whether between-limb strength differences influenced preferential limb use during the transition between gait and STA. It was hypothesised that, should a large between-limb strength difference exist, one limb would be used preferentially to perform either the 1-step or 2-step transition from level into STA gait.

METHODS

PARTICIPANTS

Following NHS ethical approval (Ref: 08-H1305-91), thirty-six participants were recruited through the local community [Mean(SD) age:71.3(7.3) years, range:60-83 years, height:163.1(6.6) cm, mass:70.4(12.7) kg] and written informed consent was obtained. Participants were pre-screened and excluded if they had any cardiovascular, musculoskeletal or neurological diseases, or a history of falls.

PROCEDURES

A biomechanical comparison of the 2-step transitioning and continuous STA cycles was performed. Lower limb segments were modelled using a six degrees-of-freedom marker set (Cappozzo et al., 1995). A custom-built 3-step wooden staircase was used (step height: 20 cm, tread: 25 cm, width: 80 cm) with a final tread of 80 cm. Handrails were available for safety reasons, but no participant used them. Kinematic data were obtained at 100Hz using 14 ProReflex cameras (Qualisys, Sweden). Ground reaction forces (GRF) were obtained from complete foot contacts made on two piezoelectric platforms (Model 9286AA, Kistler, Switzerland) sampling at 500 Hz. One platform was embedded into a concrete pit in the ground before the staircase and another was mounted into the first step which was an independent structure separate to the remainder of the staircase (Figure 1). The influence of alternate platform mountings (wooden *vs.* concrete) and the staircase structure (vibrations) on the kinetic data obtained was assessed using fast-Fourier transformation (Chesters et al., 2013). This analysis indicated that the error induced by staircase mounting was negligible: <2.2 % of the total power was lost, but only at higher frequencies (18 Hz) than those exhibited during gait (<10 Hz) (Wearing et al., 2003).

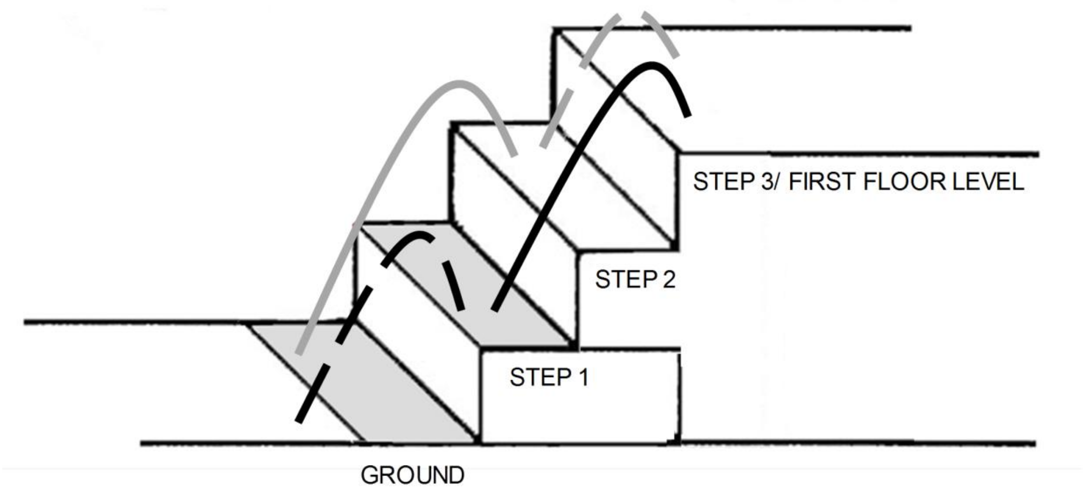

FIGURE 1 Experimental staircase set-up presenting the 1-step (dashed) and the 2-step (solid) gait cycles during STA

Complete 2-step gait cycles selected for analysis were the transitioning cycle between ground level and step 2 (solid grey line) and a continuous STA gait cycle from step 1 to step 3 (solid black line)

The dashed lines represent the 1-step gait cycles (not analysed in the current study), and the solid lines represent the 2-step gait cycles that were selected for further analysis. The grey shaded steps denote the positioning of force plates for kinetic data acquisition of the transitioning (ground) and continuous (step 1) gait cycles

Participants walked along a 4-metre level walkway to achieve a steady-state speed prior to ascending the stairs unaided at a self-selected pace. Steady-state speeds can be reached after 2.5 metres (Lindemann et al., 2008) and therefore the walkway was considered ample room for steady-state gait to be attained. Furthermore, mechanical differences have been reported when STA is initiated from walking or from a standing position, such that hip and knee joint biomechanics are underestimated in the latter case (Vallabhajosula et al., 2011).

Due to the critical role of the knee joint during STA in older adults (Reeves et al., 2009), peak dynamometry-derived (Biodex System 3, Biodex Medical, Shirley, NY) knee flexion and extension moments were used to quantify between-limb strength differences. Participants were seated with a hip flexion angle of 90° and performed five consecutive maximal voluntary concentric knee extension-flexion trials through the full ROM at 180°/sec. The sample had a mean knee ROM of ~98° (16SD). Participants performed several warm-up trials before gravity-corrected joint moments were recorded. Due to technical failure, strength data for four participants were excluded (n=32).

GAIT VARIABLES

Temporal-spatial parameters including gait speed (m/s), stance phase duration (%) and cycle time (s) are presented. Sagittal angles of the hip, knee and ankle joints were normalised to 100 % gait cycle (stance and swing). Joint ROM was calculated as the range between the peak flexor/ extensor angle observed. The following peak orthogonal GRFs (N) were analysed: medial (Fx1), lateral (Fx2), posterior (Fy1), anterior (Fy2), and vertical forces achieved in the first and latter part of stance (Fz1 and Fz3, respectively), and the minimum vertical GRF achieved mid-stance (Fz2). Loading and decay rates (N/kg/s) were determined using the positive slope from initial contact to Fz1 and the negative slope from Fz3 to toe-off, respectively. Kinetic data were normalised to mass (kg) and presented for the gait cycle except for GRF parameters which were time normalised to stance. Peak moments and power bursts were defined for the lower limb joints (Vanicek et al., 2010) and presented as 100% gait cycle. The only exception was the A2 power burst, which indicated power absorption during the pull-up phase in this study. This was in contrast to previous findings that showed the second power burst as power generation (McFadyen and Winter, 1988; Vanicek et al., 2010).

DATA ANALYSIS

Marker trajectories were identified and data were exported to Visual 3D (C-Motion, Rockville, MD, USA). A cubic-spline algorithm was used to interpolate the kinematic data over a maximum gap of 10 frames. Kinematic and kinetic data were filtered using a low-pass Butterworth filter with a cut-off frequency of 6Hz and 25Hz, respectively (Siegel et al., 1996). The 2-step transitioning cycle began on the floor and ended on step 2 (Figure 1). The 2-step continuous STA cycle began on step 1 and ended on step 3. Gait events (first foot contact and toe-off) of both the continuous and transitioning cycle were identified using the kinetic data from the platform embedded in the first step and level ground, respectively. The foot contact terminating the gait cycle for each limb was identified by examining the kinematic profile of the 1st metatarsal marker, as most participants made initial contact with the forefoot.

LIMB PREFERENCE DURING THE GAIT-TO-STAIR TRANSITION

Participants were not notified that limb preference was being observed. Participants self-selected their starting position for each trial beyond 4-metres of the staircase, which removed any potential bias introduced by standardising this position, and enabled steady-state gait speed to be achieved. The limb used (right or left) to execute the 2-step transitioning cycle was noted and participants were assigned to one of the following groups: if they (a) had no limb preference during the 2-step transition, thus using each limb interchangeably *(bilateral)*; (b) used their right limb consistently to complete the 2-step transition *(unilateral-right)*; and (c) used their left limb consistently to complete the 2-step transition *(unilateral-left)*. If a participant used a different limb for at least one trial, they were categorised into the bilateral group. Participants completed 8-10 trials depending on functional ability. The bilateral group displayed a mean ratio of 54/46% split of left/right limb preference during the 2-step transition.

STATISTICAL ANALYSES

Aim 1: Transitioning vs. continuous ascent

Paired samples t-tests assessed the biomechanical differences between the 2-step transitioning and continuous STA cycles.

Aim 2: Limb preference during the gait-to-stair transition

Using the stronger *vs.* weaker limb strength values, data for the unilateral limb preference groups were combined. Statistical inferences were made between the *bilateral* and the *combined unilateral* limb preference groups. Independent samples t-tests evaluated the between-group (bilateral/ combined unilateral) differences in dynamometer-derived maximal knee flexor and extensor strength.

All statistical analyses were performed using PASW v18.0 software (SPSS Inc., IL), with significance accepted at $P \leq 0.05$. Normality was assessed using the difference between the biomechanical variables selected for the continuous and transitioning cycles and this was satisfied in all cases. A family-wise Hommel correction was used to manage the type I error associated with multiple comparisons (Hommel, 1988). Where statistical differences were found, Cohen's d effect sizes (d) were calculated to verify these differences.

RESULTS

TRANSITIONING *vs.* CONTINUOUS ASCENT

Significant differences were observed between the temporal-spatial parameters of the 2-step transitioning and continuous STA cycles (Table 1). The continuous STA cycle (step 1 to 3) was completed on average 23% slower, with an increased cycle time (7%) and stance phase duration (3%, $P \leq 0.004$). Significantly greater hip flexion (stance) and knee flexion (mid-swing) were observed during the continuous STA cycle. In contrast the 2-step transitioning cycle demanded a larger ankle ROM (Table 1 and Figure 2). Significant kinetic differences ($P \leq 0.018$) were identified between the 2-step transitioning and continuous STA cycles (Table 2). The continuous STA cycle demonstrated greater contributions from the hip, as evidenced by a greater hip extensor moment (Figure 3), power generation during weight-acceptance (H1), and significantly larger knee power bursts (K1 generation and K3 absorption, Figure 3). Increased GRF parameters (lateral (Fx2), posterior (Fy1), anterior (Fy2), vertical forces (Fz1 and Fz3), and load rate), larger hip flexor and ankle dorsiflexor moments, and greater peak ankle power absorption (A2; terminal stance, $P<0.02$) were observed during the 2-step transitioning cycle. Moreover, notable (albeit non-significant) increases in ankle power generation (A3; pre-swing) and peak plantarflexor moment (pre-swing) were observed during the 2-step transitioning cycle.

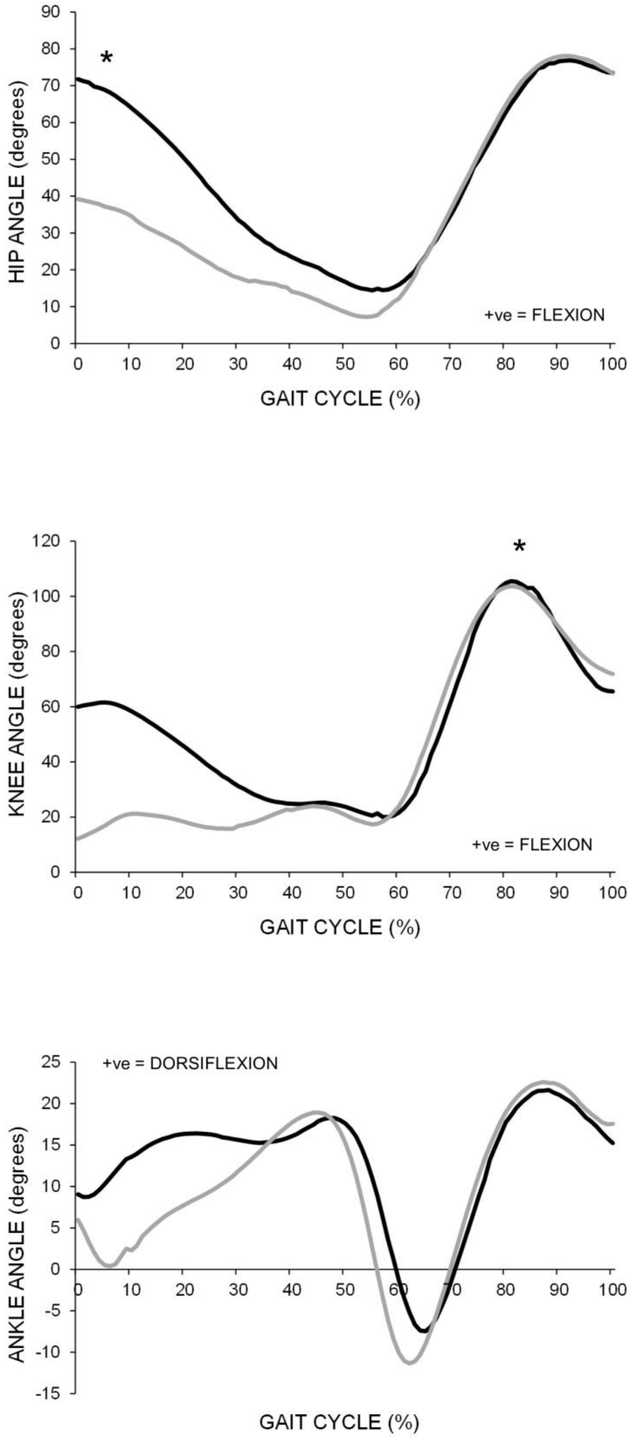

FIGURE 2 Group mean sagittal plane joint angle profiles for a 2-step transitioning STA gait (grey line) and 2-step continuous (black line) cycle

* indicates significance post-corrective procedures (P < .002)

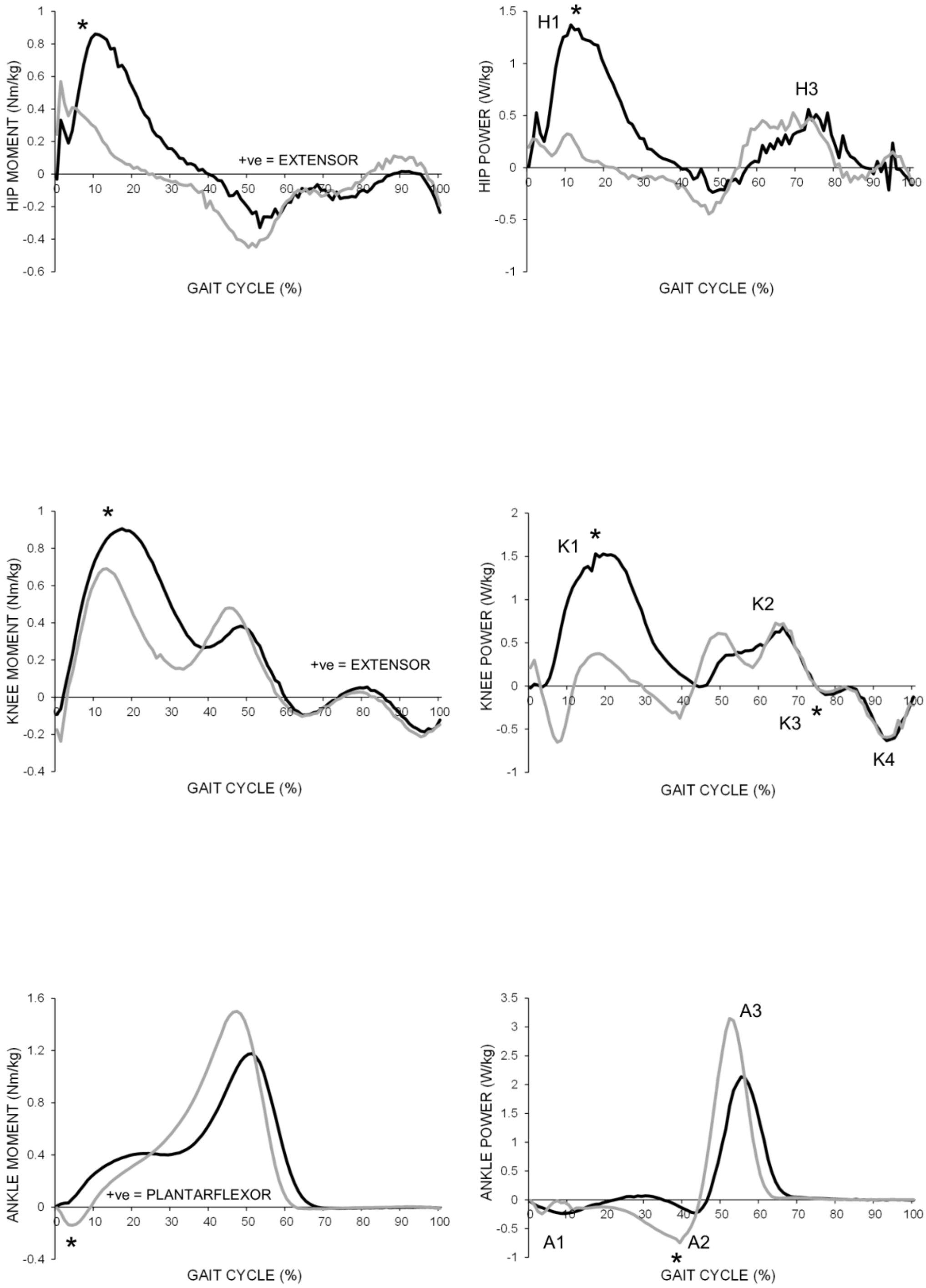

FIGURE 3 Group mean sagittal plane joint moment and power profiles for a 2-step transitioning STA gait (grey line) and 2-step continuous (black line) cycle

* indicates significance post-corrective procedures (P < .002)

LIMB PREFERENCE DURING THE GAIT-TO-STAIR TRANSITION

The *bilateral* group (no limb preference) was larger (n=20) and significantly older than the *combined unilateral* group (n=16; Figure 4 and Table 3). The relative strength differences between the strongest and weakest limbs were small in the *bilateral* group (flexors d=.40; extensors d=.25), but much larger in the *combined unilateral* group, especially for the knee extensors (flexors d=.49; extensors d=.51) (see stronger vs. weaker in Figure 4 and Table 3). The only significant between-group (bilateral *vs.* combined unilateral) difference highlighted that peak knee flexor moments of the strongest leg were significantly larger for the *combined unilateral* group compared with the *bilateral* group (d=.85, *P*=.032). Most of the participants in the *unilateral* limb preference group (>71%) used the stronger limb to complete the 2-step transition in every trial, the remaining participants used the weakest limb for the 2-step transition.

TABLE 1 Mean (SD) temporal-spatial and peak joint kinematic (degrees) parameters of a 2-step continuous and a 2-step transitioning STA cycle

GAIT PARAMETERS	CONTINUOUS STA	TRANSITIONAL STA	t	CORRECTED p VALUE	COHEN'S d
TEMPORAL-SPATIAL PARAMETERS					
GAIT SPEED (m/s)	0.66 (0.1)	0.81 (0.1)	-12.407	0.002	1.01
CYCLE TIME (s)	1.4 (0.2)	1.3 (0.2)	10.842	0.002	0.66
STANCE (%)	62.0 (3.1)	60.0 (2.3)	3.128	0.004	0.68
JOINT KINEMATICS (degrees)					
HIP FLEXION (*weight acceptance*)	71.6 (8.3)	39.3 (8.1)	27.816	0.013	3.99
HIP FLEXION (*foot placement*)	77.5 (9.0)	78.3 (8.7)	-0.946	0.993	
HIP ROM	64.8 (6.4)	72.6 (7.1)	-6.899	0.013	1.16
KNEE FLEXION (*foot clearance*)	107.6 (8.1)	104.3 (9.4)	3.069	0.026	0.37
KNEE ROM	92.0 (6.8)	93.7 (7.5)	-1.511	0.509	
ANKLE DORSIFLEXION (*pull up*)	21.2 (5.2)	19.9 (5.3)	1.520	0.509	
ANKLE PLANTARFLEXION (*forward continuance*)	-10.0 (6.7)	-12.7 (6.6)	2.590	0.071	
ANKLE DORSIFLEXION (*foot clearance*)	22.6 (7.2)	23.4 (7.1)	-1.012	0.993	
ANKLE ROM	34.0 (7.4)	37.6 (6.2)	-3.069	0.026	0.53

Limb data are presented as mean (SD). ROM denotes range of motion. Shaded areas indicate the gait cycle (continuous *vs.* transitioning) that displayed the parameter of largest magnitude ($P < .05$). Hip and knee flexion, and ankle dorsiflexion angles are positive.

TABLE 2 Mean (SD) GRF and peak joint kinetic parameters of a 2-step continuous and a 2-step transitioning STA cycle

GAIT PARAMETERS	CONTINUOUS STA	TRANSITIONAL STA	t	CORRECTED p VALUE	COHEN'S d
GROUND REACTION FORCES (N/kg) and GRF RATES (N/kg/sec)					
MEDIAL Fx1 GRF	0.03 (0.01)	0.03 (0.02)	-0.445	1.000	
LATERAL Fx2 GRF	-0.06 (0.02)	-0.06 (0.02)	2.095	0.279	
POSTERIOR Fy2 GRF	-0.12 (0.03)	-0.17 (0.06)	5.055	0.010	1.07
ANTERIOR Fy2 GRF	0.07 (0.02)	0.12 (0.03)	-10.116	0.010	1.99
VERTICAL Fz1 GRF	1.02 (0.06)	1.17 (0.09)	-7.372	0.010	2.00
VERTICAL Fz2 GRF	0.73 (0.07)	0.75 (0.08)	-1.092	1.000	
VERTICAL Fz3 GRF	1.24 (0.09)	1.31 (0.13)	-2.998	0.045	0.67
LOAD RATE	3.79 (1.19)	6.37 (1.72)	-10.260	0.010	1.78
DECAY RATE	7.78 (1.41)	8.22 (2.17)	-1.480	0.760	
JOINT MOMENTS (Nm/kg)					
HIP EXTENSOR (*weight acceptance*)	0.93 (0.35)	0.66 (0.22)	-4.204	0.010	0.94
HIP FLEXOR (*forward continuance*)	-0.49 (0.23)	-0.66 (0.27)	-2.801	0.065	
KNEE EXTENSOR (*weight acceptance*)	0.91 (0.32)	0.77 (0.31)	1.986	0.323	
KNEE FLEXOR (*forward continuance*)	-0.23 (0.09)	-0.31 (0.12)	3.005	0.045	0.77
ANKLE DORSIFLEXOR (*weight acceptance*)	-0.04 (0.04)	-0.13 (0.11)	-6.705	0.010	1.11
ANKLE PLANTARFLEXOR (*forward continuance*)	1.29 (0.38)	1.54 (0.26)	2.766	0.065	
JOINT POWERS (W/kg)					
H1 HIP POWER GENERATION (*weight acceptance*)	1.83 (1.11)	0.58 (0.33)	5.107	0.010	1.56
H3 HIP POWER GENERATION (*foot clearance*)	0.80 (0.43)	0.81 (0.34)	-0.028	1.000	
K1 KNEE POWER GENERATION (*weight acceptance*)	1.70 (0.64)	0.58 (0.27)	9.243	0.010	2.33
K2 KNEE POWER GENERATION (*foot clearance*)	1.25 (0.98)	1.00 (0.36)	1.159	1.000	
K3 KNEE POWER ABSORPTION (*foot clearance*)	-0.29 (0.20)	-0.16 (0.12)	-3.626	0.018	0.81
K4 KNEE POWER ABSORPTION (*foot placement*)	-0.85 (0.42)	-0.77 (0.39)	-1.347	0.916	
A1 ANKLE POWER ABSORPTION (*pull up*)	-0.36 (0.36)	-0.37 (0.18)	0.185	1.000	
A2 ANKLE POWER ABSORPTION (*pull up*)	-0.56 (0.39)	-0.86 (0.34)	4.696	0.010	0.84
A3 ANKLE POWER GENERATION (*forward continuance*)	3.40 (0.90)	3.76 (1.12)	-1.859	0.395	

Shaded areas indicate the gait cycle (continuous *vs.* transitioning) that displayed the parameter of largest magnitude ($P < .05$). Positive [+] joint moments indicate extensor moments at the hip and knee, and plantarflexor muscle involvement at the ankle. Positive [+] joint powers indicate power generation and negative [-] powers indicate power absorption. Hip power peaks of absorption (terminal stance; H2) and generation (terminal swing; H4) were not included as these power bursts were considered minimal and varied greatly in comparison to H1 and H3 power generation (mid-stance and mid-swing, respectively)

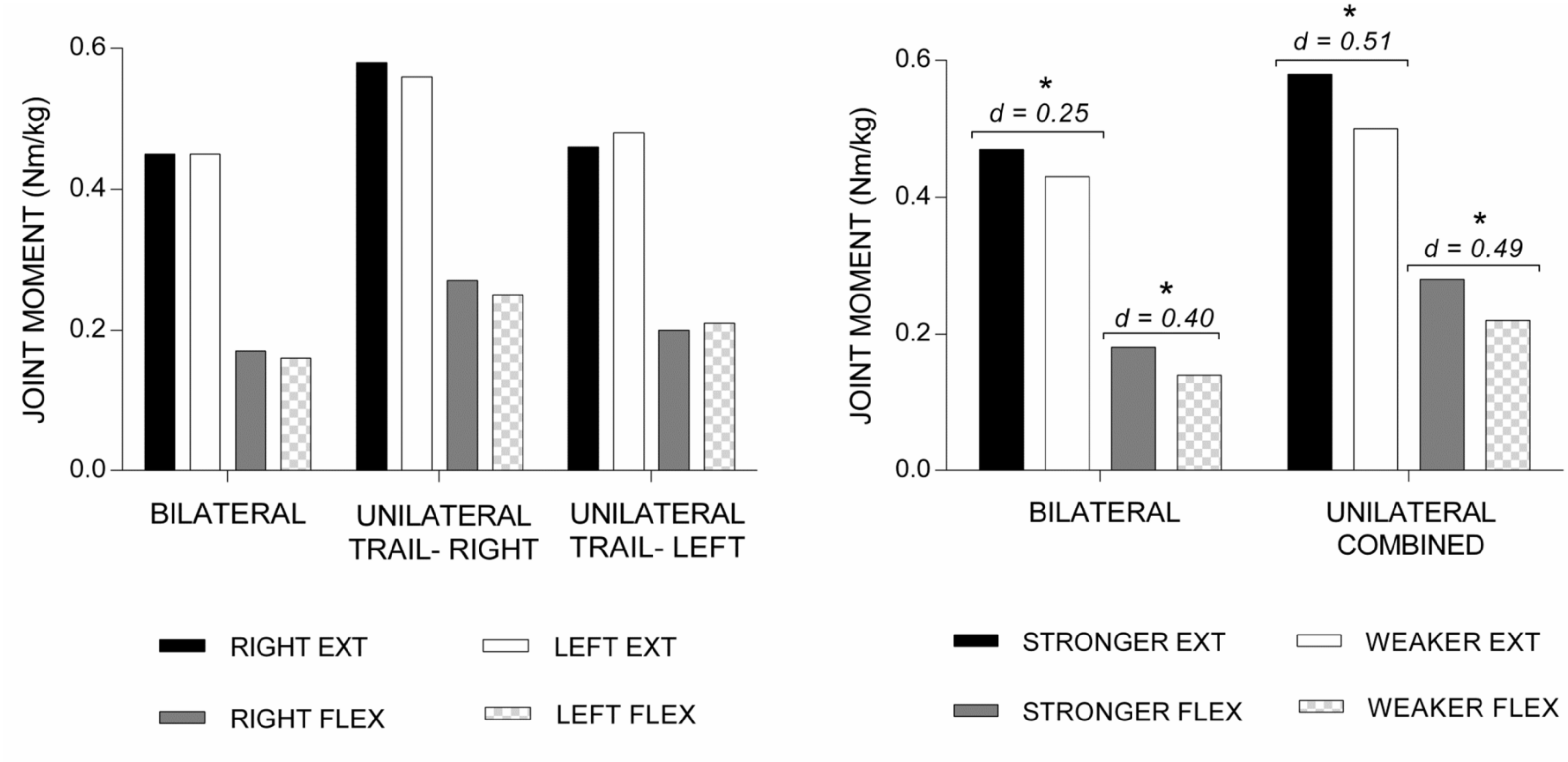

FIGURE 4 Participant characteristics and normalised peak dynamometer-derived knee moments (Nm/kg) for each of the limb preference groups

* indicates significant differences detected between stronger and weaker limbs ($P \leq .002$). Cohen's d effect size (d) are presented where statistical comparisons were made

TABLE 3 Mean (SD) participant characteristics according to the limb preference groups

		BILATERAL	UNILATERAL COMBINED	UNILATERAL: - RIGHT	UNILATERAL: - LEFT
n		20	16	10	6
AGE (years) *		75.0 (5.7)	66.6 (6.4)	63.7 (2.8)	71.5 (8.0)
HEIGHT (m)		1.62 (0.07)	1.64 (0.06)	1.64 (0.06)	1.64 (0.07)
MASS (kg)		67.2 (12.4)	74.5 (12.2)	74.3 (14.1)	74.8 (9.4)
KNEE EXTENSORS (Nm/kg)	RIGHT	0.45 (0.18)	NR	0.60 (0.16)	0.43 (0.18)
	LEFT	0.45 (0.15)	NR	0.59 (0.16)	0.45 (0.08)
KNEE FLEXORS (Nm/kg)	RIGHT	0.17 (0.11)	NR	0.30 (0.15)	0.17 (0.13)
	LEFT	0.16 (0.10)	NR	0.28 (0.09)	0.17 (0.11)
KNEE EXTENSORS (Nm/kg)	STRONGER *	0.47 *($CI_{95\%}$ = 0.39:0.56)*	0.58 *($CI_{95\%}$ = 0.48:0.67)*		
	WEAKER *	0.43 *($CI_{95\%}$ = 0.35:0.51)*	0.50 *($CI_{95\%}$ = 0.42:0.58)*		
KNEE FLEXORS (Nm/kg)	STRONGER *	0.18 *($CI_{95\%}$ = 0.13:0.24)*	0.28 *($CI_{95\%}$ = 0.20:0.35)*		
	WEAKER *	0.14 *($CI_{95\%}$ = 0.09:0.19)*	0.22 *($CI_{95\%}$ = 0.15:0.29)*		

* indicates significant differences at alpha p≤0.05 using the grouped (shaded) data, NR denotes not relevant comparison, $CI_{95\%}$ denotes the 95% confidence interval

DISCUSSION

The present study investigated the biomechanical characteristics of the transitioning and continuous STA cycles, both of which covered a vertical displacement of two steps. Numerous biomechanical differences were observed between these steps, in a sample of healthy older women, illustrating the contrast in mechanical demands according to functional task. This study was the first to explore the influence of between-limb strength differences on limb preference during the gait-to-STA transition. We found that when a large between-limb knee extensor strength difference existed, most of the older women preferentially selected the strongest limb to complete the 2-step transition between level and STA gait.

TRANSITIONING *vs.* CONTINUOUS ASCENT

To the best of the authors' knowledge, no previous study has provided a fully comprehensive analysis of the differences between the 2-step STA cycles (transitioning *vs.* continuous) in older women. Andriacchi *et al.* (1980) found that, for young men, continuous STA demanded increased knee flexion and ankle plantarflexion, and larger external hip and knee flexor moments compared to the 2-step transitioning cycle, but these differences were not confirmed statistically. Our findings corroborate the increased knee flexion during continuous STA but conversely we showed that the 2-step transitioning cycle exhibited increased peak ankle plantarflexion compared to continuous STA, however this difference was not significant post-corrective procedures (P=.071).

On the whole, peak GRF parameters (lateral (Fx2), posterior (Fy1), anterior (Fy2), vertical forces (Fz1 and Fz3) and load rate), and ankle joint kinetics were larger during the 2-step transitioning cycle. In combination, the greater speed and forces indicated greater propulsive requirements of the limb completing the 2-step transitioning cycle compared to that required during reciprocal, continuous STA. The increased speed observed during the 2-step transitioning cycle are in agreement with previous work (Lee and Chou, 2007) and likely reflect the need to transfer whole-body momentum from gait to STA. Older adults ascend stairs at a slower speed compared to level gait (DeVita and Hortobagyi, 2000; Stacoff et al., 2005). Therefore, upon approaching the stairs, the limb completing the second half of the gait-to-STA transition generates greater propulsion through increased ankle ROM and power generation (Table 1 and 2; labelled A3). Furthermore the significantly increased eccentric activity at the ankle (Table 2 and Figure 3; labelled A2), during pull-up for the transitioning cycle is also in contrast to the concentric power burst reported previously in the literature (McFadyen and Winter, 1988; Vanicek et al., 2010). This difference likely acts to control and slow the advancement of the shank over the foot and may be indicative of concentric plantarflexor weakness as observed for older adults (DeVita and Hortobagyi, 2000; Judge et al., 1996; Lewis and Ferris, 2008). Considering the quicker velocity ($P<.002$) observed in combination with the increased forces and reliance on concentric knee extensor activity, construction of an extended handrail structure surrounding the area preceding the stairs may be beneficial, providing an additional point of contact during this biomechanically demanding transition.

Kinetic differences between the transitioning and continuous STA cycles represent the contrast in functional demands. Joint powers during early stance suggested distinct strategies were employed to manage weight-acceptance and pull-up during both of the STA cycles analysed. Reduced internal flexor moments at the hip and knee during weight-acceptance were shown during the 2-step transitioning cycle and a small peak dorsiflexor moment, significantly larger than that of the continuous STA cycle (P=.011), was observed. At initial contact, the kinematics and kinetics of the 2-step transitioning and continuous STA cycles differed significantly such that the former exhibited a small dorsiflexor moment, similar to that observed during gait, as in fact initial contact occurred on level ground before the staircase. Conversely, for continuous STA, initial contact was made with the forefoot. However, during the swing phase, both analysed cycles conformed to similar mechanics, which were imposed by the staircase dimensions and structure.

LIMB PREFERENCE DURING THE GAIT-TO-STAIR TRANSITION

The results of this study have shown that both *unilateral* limb preference groups demonstrated larger between-limb knee extensor strength differences (13.8%), and more commonly relied upon the strongest limb (in terms of knee extensor strength) to complete the 2-step transitioning cycle. In contrast, the *bilateral* preference group had smaller between-limb knee extensor strength differences (8.5%) and showed no consistent limb preference (Figure 4). These findings are in contrast to current rehabilitation practice that advocates the use of the stronger limb to complete the initial 1-step transition in individuals with considerably reduced (e.g., very frail, sarcopenic) and/or asymmetric musculoskeletal capacities (e.g., lower-limb amputees). Such recommendations possibly exist because the limb completing the initial 1-step transition experiences considerable loading (McFadyen and Winter, 1988). Although the exact reason for this stronger-limb 2-step transitioning strategy remains unclear, it may be speculated that it allows the stronger limb to generate the necessary propulsion to ascend two steps (Figure 3; A3) and transfer the increased momentum from gait into STA. While the stronger limb completing the 2-step transition provides considerable propulsion (pre-swing), the weaker limb positioned on step 1 prepares for single-limb support by providing adequate stability evidenced by peaks in hip and knee power generation (Figure 3; H1 and K1).

During STA, the musculature at the knee is required to produce joint moments to compensate for ankle joint weakness, and as such, knee strength is critical in successful STA (Reeves et al., 2009). This study quantified between limb strength differences from measurements at the knee. However, this may miss important differences at the hip and ankle. Although it cannot be ruled out that the few *unilateral* participants who adopted a weaker-limb 2-step transitioning strategy represent natural variation from the more common stronger-limb 2-step transitioning strategy, it is possible that between limb strength differences at other joints may account for this discrepancy. Further work is required to determine the extent to which preferential stepping strategies are utilised and the musculoskeletal characteristics that distinguish these individuals.

It is noteworthy that the *bilateral* limb preference group was significantly older than the *combined unilateral* group and displayed reduced dynamometer-derived peak knee moments. Interestingly, additional bivariate correlations revealed a non-significant trend towards a reduction in between-limb strength differences with advancing age (extensor=.25, P=.163; flexor=.32, P=.071). This suggests that, with advancing age, the between-limb knee strength differences were smaller and neither limb was preferentially selected for either task.

In light of these findings, recommendations to improve stair performance should consider between-limb differences and age-induced changes. Recent research has suggested that strength differences may contribute to gait asymmetry (Dessery et al., 2011). However in another study we conducted with the same sample of participants, gait was deemed symmetrical (Alcock et al., 2013). Therefore, we do not believe locomotor asymmetry influenced limb preference in the current study, and between-limb strength differences remain the likely explanation for the preferential limb choice strategies observed. However, our method for categorising participants into the two discrete preference groups may have simplified the continuous nature of preferential limb use and its relationship to between-limb strength differences.

The conclusions drawn from this study of healthy older women concerning the differences between transitioning and continuous STA provide a baseline from which age-related dysfunction may be identified. In the present study, the foot contact that terminated the continuous STA step occurred on the top of the 3-step staircase and, thus, foot position may have differed from continuous STA using a larger staircase. However, since data beyond foot contact on this step were not considered and an additional step was required by the contralateral limb to reach the top of the staircase, it is expected that this influence would be minimal on the gait cycles studied here.

CONCLUSIONS

Key differences, particularly during stance, were identified with the transitioning cycle requiring greater lower limb ROM and increased effort from the ankle plantarflexors. Conversely, increased hip and knee extensor activity were observed during continuous STA. The functional roles of contrasting muscle groups during the execution of the distinct STA cycles should be recognised during exercise strengthening programmes, thus helping older adults to maintain adequate locomotor function during STA. The gait mechanics of either limb are commensurate with varying stability and propulsive roles while completing the high risk transition between gait and STA. Moreover, this study has shown that most individuals with large between-limb strength differences adopted a preferential stronger-limb 2-step transitioning strategy, which contrasts STA patterns recommended to other clinical populations. This allowed the stronger limb to generate the high levels of propulsion required during the 2-step transitioning cycle transferring whole-body momentum from gait to STA. Further work is required to fully understand the stepping strategies and preferential limb use of older adults upon approaching stairs.

REFERENCES

Alcock, L., Vanicek, N., O'Brien, T.D., 2013. Alterations in gait speed and age do not fully explain the changes in gait mechanics associated with healthy older women. Gait & Posture *37*, 586-592.

Andriacchi, T.P., Andersson, G.B., Fermier, R.W., Stern, D., Galante, J.O., 1980. A study of lower-limb mechanics during stair-climbing. The Journal of Bone and Joint Surgery 62, 749-757.

Benedetti, M., Berti, L., Maselli, S., Mariani, G., Giannini, S., 2007. How do the elderly negotiate a step? A biomechanical assessment. Clinical Biomechanics 22, 567-573.

Bertucco, M., Cesari, P., 2009. Dimensional analysis and ground reaction forces for stair climbing: effects of age and task difficulty. Gait & Posture 29, 326-331.

Blake, A.J., Morgan, K., Bendall, M.J., Dallosso, H., Ebrahim, S.B.J., Arie, T.H.D., Fentem, P.H., Bassey, E.J., 1988. Falls by Elderly People at Home - Prevalence and Associated Factors. Age and Ageing 17, 365-372.

Campbell, A.J., Borrie, M.J., Spears, G.F., 1989. Risk factors for falls in a community-based prospective study of people 70 years and older. Journal of Gerontology 44, M112-117.

Cappozzo, A., Catani, F., Della Croce, U., Leardini, A., 1995. Position and orientation in space of bones during movement: anatomical frame definition and determination. Clinical Biomechanics 10, 171-178.

Chesters, T., Alcock, L., O'Brien, T.D., Vanicek, N., Dobson, C.A., 2013. Frequency domain characteristics of kinetic data from force platforms mounted in instrumented stairways, 22nd Annual Meeting of the European Society for Movement Analysis in Adults and Children, University of Strathclyde, Glasgow, Scotland.

Dessery, Y., Barbier, F., Gillet, C., Corbeil, P., 2011. Does lower limb preference influence gait initiation? Gait & Posture 33, 550-555.

DeVita, P., Hortobagyi, T., 2000. Age causes a redistribution of joint torques and powers during gait. Journal of Applied Physiology 88, 1804-1811.

Faulkner, J.A., Larkin, L.M., Claflin, D.R., Brooks, S.V., 2007. Age-related changes in the structure and function of skeletal muscles. Clinical and Experimental Pharmacology and Physiology 34, 1091-1096.

Gine-Garriga, M., Guerra, M., Mari-Dell'Olmo, M., Martin, C., Unnithan, V.B., 2009. Sensitivity of a modified version of the 'timed get up and go' test to predict fall risk in the elderly: a pilot study. Archives of Gerontology and Geriatrics 49, e60-e66.

Hamel, K.A., Cavanagh, P.R., 2004. Stair performance in people aged 75 and older. Journal of the American Geriatrics Society 52, 563-567.

Hamel, K.A., Okita, N., Bus, S.A., Cavanagh, P.R., 2005. A comparison of foot/ground interaction during stair negotiation and level walking in young and older women. Ergonomics 48, 1047-1056.

Hommel, G., 1988. A stagewise rejective multiple test procedure based on a modified Bonferroni test. Biometrika 75, 383-386.

Hughes, V.A., Frontera, W.R., Wood, M., Evans, W.J., Dallal, G.E., Roubenoff, R., Singh, M.A.F., 2001. Longitudinal muscle strength changes in older adults. Journals of Gerontology Series A: Biological Sciences and Medical Sciences 56, B209-B217.

Jackson, P.L., Cohen, H.H., 1995. An in-depth investigation of 40 stairway accidents and the stair safety literature. Journal of Safety Research 26, 151-159.

Judge, J.O., Davis, R.B., 3rd, Ounpuu, S., 1996. Step length reductions in advanced age: the role of ankle and hip kinetics. Journals of Gerontology Series A: Biological Sciences and Medical Sciences 51, M303-M312.

Kang, H.G., Dingwell, J.B., 2008. Effects of walking speed, strength and range of motion on gait stability in healthy older adults. Journal of Biomechanics 41, 2899-2905.

Lee, H.J., Chou, L.S., 2007. Balance control during stair negotiation in older adults. Journal of Biomechanics 40, 2530-2536.

Lewis, C.L., Ferris, D.P., 2008. Walking with increased ankle pushoff decreases hip muscle moments. Journal of Biomechanics 41, 2082-2089.

Lindemann, U., Najafi, B., Zijlstra, W., Hauer, K., Muche, R., Becker, C., Aminian, K., 2008. Distance to achieve steady state walking speed in frail elderly persons. Gait & posture 27, 91-96.

McFadyen, B.J., Winter, D.A., 1988. An integrated biomechanical analysis of normal stair ascent and descent. Journal of Biomechanics 21, 733-744.

Nadeau, S., McFadyen, B.J., Malouin, F., 2003. Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking? Clinical Biomechanics 18, 950-959.

Novak, A.C., Brouwer, B., 2011. Sagittal and frontal lower limb joint moments during stair ascent and descent in young and older adults. Gait & Posture 33, 54-60.

Reeves, N.D., Spanjaard, M., Mohagheghi, A.A., Baltzopoulos, V., Maganaris, C.N., 2009. Older adults employ alternative strategies to operate within their maximum capabilities when ascending stairs. Journal of Electromyography and Kinesiology 19, e57-e68.

Sheehan, R.C., Gottschall, J.S., 2012. At similar angles, slope walking has a greater fall risk than stair walking. Applied Ergonomics 43, 473-478.

Siegel, K.L., Kepple, T.M., Caldwell, G.E., 1996. Improved agreement of foot segmental power and rate of energy change during gait: inclusion of distal power terms and use of three-dimensional models. Journal of Biomechanics 29, 823-827.

Stacoff, A., Diezi, C., Luder, G., Stussi, E., Kramers-de Quervain, I.A., 2005. Ground reaction forces on stairs: effects of stair inclination and age. Gait & Posture 21, 24-38.

Templer, J., 1978. An analysis of the behavior of stair users.

Templer, J., 1992. The staircase. MIT Press, Cambridge, MA.

Vallabhajosula, S., Yentes, J.M., Momcilovic, M., Blanke, D.J., Stergiou, N., 2011. Do lower-extremity joint dynamics change when stair negotiation is initiated with a self-selected comfortable gait speed? Gait & Posture 35, 203-208.

Vanicek, N., Strike, S.C., McNaughton, L., Polman, R., 2010. Lower limb kinematic and kinetic differences between transtibial amputee fallers and non-fallers. Prosthetics and Orthotics International 34, 399-410.

Wearing, S., Smeathers, J., Urry, S., 2003. Frequency-domain analysis detects previously unidentified changes in ground reaction force with visually guided foot placement. Journal of Applied Biomechanics 19, 71-78.

Wilken, J.M., Sinitski, E.H., Bagg, E.A., 2011. The role of lower extremity joint powers in successful stair ambulation. Gait & Posture 34, 142-144.

Wyatt, J.P., Beard, D., Busuttil, A., 1999. Fatal falls down stairs. Injury 30, 31-34.