Does a Microprocessor-controlled Prosthetic Knee Affect Stair Ascent Strategies in Persons With Transfemoral Amputation?

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Abstract

Background Stair ascent can be difficult for individuals with transfemoral amputation because of the loss of knee function. Most individuals with transfemoral amputation use either a step-to-step (nonreciprocal, advancing one stair at a time) or skip-step strategy (nonreciprocal, advancing two stairs at a time), rather than a step-over-step (reciprocal) strategy, because step-to-step and skip-step allow the leading intact limb to do the majority of work. A new

microprocessor-controlled knee (Ottobock X2®) uses flexion/extension resistance to allow step-over-step stair ascent.

Questions/Purposes We compared self-selected stair ascent strategies between conventional and X2® prosthetic knees, examined between-limb differences, and differentiated stair ascent mechanics between X2® users and individuals without amputation. We also determined which factors are associated with differences in knee position during initial contact and swing within X2® users.

Methods Fourteen individuals with transfemoral amputation participated in stair ascent sessions while using conventional and X2® knees. Ten individuals without amputation also completed a stair ascent session. Lower-extremity stair ascent joint angles, moment, and powers and ground reaction forces were calculated using inverse dynamics during self-selected strategy and cadence and controlled cadence using a step-over-step strategy.

Results One individual with amputation self-selected a step-over-step strategy while using a conventional knee, while 10 individuals self-selected a step-over-step strategy while using

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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X2[®] knees. Individuals with amputation used greater prosthetic knee flexion during initial contact (32.5°, $p = 0.003$) and swing (68.2°, $p = 0.001$) with higher intersubject variability while using X2[®] knees compared to conventional knees (initial contact: 1.6°, swing: 6.2°). The increased prosthetic knee flexion while using X2[®] knees normalized knee kinematics to individuals without amputation during swing (88.4°, $p = 0.179$) but not during initial contact (65.7°, $p = 0.002$). Prosthetic knee flexion during initial contact and swing were positively correlated with prosthetic limb hip power during pull-up ($r = 0.641$, $p = 0.046$) and push-up/early swing ($r = 0.993$, $p < 0.001$), respectively.

Conclusions Participants with transfemoral amputation were more likely to self-select a step-over-step strategy similar to individuals without amputation while using X2[®] knees than conventional prostheses. Additionally, the increased prosthetic knee flexion used with X2[®] knees placed large power demands on the hip during pull-up and push-up/early swing. A modified strategy that uses less knee flexion can be used to allow step-over-step ascent in individuals with less hip strength.

Level of Evidence Level II, therapeutic study. See Instructions for Authors for a complete description of levels of evidence.

Introduction

Stairs are often encountered in daily living and require greater lower-extremity ROM and strength to negotiate, compared to level ground walking [1, 6, 11, 15]. Stair ascent may be challenging for individuals with above-the-knee (transfemoral) amputation because of the importance of knee ROM and extensor muscles in stair ascent [10]. Recent developments in microprocessor knee technologies have attempted to optimize stair and ramp ascent [4], whereas previous developments have primarily focused on level ground walking and descending stairs and ramps [13, 20].

Individuals without amputation typically ascend stairs using a step-over-step (reciprocal) strategy (Fig. 1A) consisting of five phases: (1) weight acceptance, (2) pull-up, (3) forward continuance, (4) push-up, and (5) swing (Fig. 2) [10, 19]. The knee plays a critical role in the pull-up and swing phases [10]. During pull-up, as the individual transitions onto the lead limb, knee extensor torque and power generation are used to lift the body upward. Additionally, lead limb hip extension power and trail limb ankle plantarflexion power aid in the transition from double- to single-limb support. During swing, positive knee and hip power are used to initiate knee flexion [10]. Individuals with transfemoral amputation are less able to ascend stairs

Fig. 1A–C The three most commonly used stair ascent strategies by individuals with transfemoral amputation are (A) step-over-step, (B) step-to-step, and (C) skip-step. The highlighted (right) limb and arrows illustrate the progression of the prosthetic limb during each stair ascent strategy. The nonhighlighted (left) limb represents the intact limb.

using a step-over-step strategy because of the inability to produce power at the knee [2, 3, 16].

Therefore, most individuals with transfemoral amputation use a step-to-step strategy (Fig. 1B) in which the leading intact limb advances to the next step and the trailing prosthetic limb follows to the same step. This strategy allows the leading intact limb to do the majority of the effort. In individuals without amputation, during step-to-step stair ascent gait, a large knee extensor moment and power generation are observed in the lead limb but not in the trail limb, indicating that the lead and trail limbs act as working and supporting limbs, respectively [14]. However,

Fig. 2A–E The five phases of the step-over-step stair ascent cycle are (A) weight acceptance, (B) pull-up, (C) forward continuance, (D) push-up, and (E) swing. The highlighted (blue, right) limb represents the limb that is in each phase of the stair ascent cycle.

this strategy is typically slower than other strategies [2, 3, 14]. To keep pace with individuals without amputation, some individuals with transfemoral amputation elect to use a skip-step strategy in which the leading intact limb advances two steps and the trailing prosthetic limb follows to the same step (Fig. 1C). This strategy results in approximately three times greater intact limb knee and hip extensor muscle activity than using a step-to-step strategy, placing greater loads on the intact knee and hip [2]. Despite having limitations, step-to-step and skip-step strategies are more commonly used by individuals with transfemoral amputation because they require less prosthetic knee ROM and power than the step-over-step strategy [14].

A new FDA-approved microprocessor-controlled prosthetic knee (X2[®]; Ottobock, Duderstadt, Germany) was developed to reduce reliance on alternate strategies and allow individuals with transfemoral amputation to ascend stairs using a step-over-step strategy. The X2[®], designed to include a more robust frame and water resistance for military use, is otherwise similar in function to the Genium[®] (Ottobock), which is commercially available to civilians. The X2[®] uses activity recognition and variable flexion/extension resistance during step-over-step stair ascent to allow individuals with transfemoral amputation to load the knee while flexed without collapsing. Body elevation is achieved through prosthetic limb hip extension and contralateral intact ankle plantarflexion [5, 6]. Previous microprocessor-controlled knees, such as the C-Leg[®] (Ottobock), do not provide sufficient resistance to prevent the knee from buckling while loaded in a flexed position. However, it is unknown whether changes in microprocessor-controlled prosthetic knee design that resulted in the X2[®] normalize stair biomechanics.

We had three primary purposes: (1) to compare self-selected stair ascent strategies between conventional and X2[®] prosthetic knees, (2) to examine between-device and between-limb biomechanical differences, and (3) to determine whether the use of the X2[®] knee restored stair ascent

mechanics compared to individuals without amputation. Additionally, after observing a wide range of step-over-step techniques for stair ascent, we determined the extent to which positioning and movement of the prosthetic limb was associated with muscular demands of the activity.

Patients and Methods

Participants

Fourteen active male individuals with unilateral transfemoral amputation participated in the study. The study was approved by the local institutional review board and all participants provided written informed consent. Participants had a mean age of 31.1 years (SD, 5.3 years), a mean body mass of 87.9 kg (SD, 11.0 kg), and a mean height of 1.79 m (SD, 0.06 m) (Table 1). All participants were at least 6 months postamputation and had been ambulating without the use of an assistive device for a minimum of 3 months. Additionally, participants were able to independently ambulate for 5 minutes continuously and had no injuries to the intact joints that would limit normal ROM. Data were also obtained from 10 weight- ($\pm 10\%$), height- ($\pm 5\%$), and sex-matched individuals without amputation for biomechanical comparison. These participants had a mean age of 25.3 years (SD, 7.3 years), a mean body mass of 83.8 kg (SD, 8.9 kg), and a mean height of 1.80 m (SD, 0.04 m) (Table 1).

Protocol

Participants with unilateral transfemoral amputation reported to the laboratory for two separate biomechanical stair ascent assessments, the first wearing their conventional knee and the second wearing the X2[®] knee. Their conventional knee was either the microprocessor-controlled

Table 1. Subject demographics for both individuals with transfemoral amputation and the matched control subjects without amputation

Individuals with transfemoral amputation						Matched controls without transfemoral amputation			
Participant	Age (years)	Mass (kg)	Height (m)	BMI	Conventional knee	Age (years)	Mass (kg)	Height (m)	BMI
P01	25	72.7	1.68	25.80	C-Leg®	24	78.6	1.73	26.3
P02*	32	103.2	1.85	30.20	C-Leg®				
P03†	36	93.8	1.78	29.60	Total Knee®				
P04	28	78.8	1.75	25.70	C-Leg®	23	77.7	1.78	24.5
P05	39	104.0	1.83	31.10	C-Leg®	21	93.4	1.82	28.2
P06†	27	82.8	1.85	24.20	Total Knee®				
P07	33	83.7	1.75	27.30	C-Leg®	22	82.3	1.77	26.3
P08	36	93.1	1.83	27.80	C-Leg®	21	84.5	1.81	25.8
P09	23	80.1	1.88	22.70	C-Leg®	30	72.5	1.86	21
P10	26	74.1	1.80	22.90	C-Leg®	20	79.5	1.82	24
P11*	25	81.9	1.68	29.00	C-Leg®				
P12	33	90.0	1.74	29.70	C-Leg®	27	85.0	1.75	27.8
P13	38	85.6	1.82	25.80	C-Leg®	44	80.9	1.84	23.9
P14	34	107.0	1.83	32.00	C-Leg®	21	103.9	1.83	31

* Denotes patients who were unable to ascend stairs step-over-step in the conventional knee, were not used in biomechanical analysis, and do not have a matched control; † denotes patients who started in the Total Knee®, were not used in the biomechanical analysis, and do not have a matched control.

C-Leg® (12 patients) or a mechanical knee (Total Knee®; Ossur Americas, Foothill Ranch, CA, USA) (two patients) that had been prescribed by their prosthetist (Table 1). Participants wore the X2® knee as their primary device for a mean of 130 days (SD, 41 days) before testing to allow them to use the device during daily activities, such as stair ambulation. During the acclimation period, patients were instructed by a physical therapist to ensure safe performance of a range of activities to include stair ascent. A certified prosthetist performed all prosthetic prescription and fitting. Individuals without amputation participated in an identical biomechanical stair ascent assessment.

Participants were asked to ascend a 16-step staircase (1) using a self-selected method at a self-selected cadence and (2) using a step-over-step method at a controlled cadence of 80 steps per minute. The staircase had a rise of 18 cm and a run of 26.5 cm, which complies with the International Residential Code for stairways [9]. Handrail use was permitted, as it is difficult for most individuals with transfemoral amputation to ascend stairs without the use of rails [12]. The self-selected method was evaluated using the stair assessment index in which a score of 0 means the participant is unable or refuses to climb the stairs and a score of 13 means the participant can ascend the stairs in a step-over-step manner without the use of a handrail [7]. A controlled cadence was included to minimize speed effects. Cadence was controlled by an auditory cue beeping at 80 beats per minute (TempoPerfect; NCH Software, Greenwood Village, CO, USA). If any participant with transfemoral amputation was unable to ascend the stairs in a step-over-step manner at

the controlled cadence in either device, his data were not used for between-device biomechanical comparisons. A minimum of three trials was obtained for each stair ascent condition.

During each trial, lower-extremity kinematics were tracked using a 26-camera motion capture system (Motion Analysis Corp, Santa Rosa, CA, USA) collecting at 120 Hz and a six-degree-of-freedom marker set in which 57 reflective markers defined 13 body segments [18]. Ground reaction force data from Stairs 5 to 8 were collected at 1200 Hz using an interlaced stairway design in which force data were obtained from four steps using two force plates (AMTI Inc, Watertown, MA, USA) [17].

Data Analysis

A fourth-order low-pass Butterworth filter was used to filter marker trajectory data (6 Hz) and analog force data (50 Hz). Heel strikes were determined by force plate data and visually verified within Visual3D™ (C-Motion Inc, Rockville, MD, USA). Lower-extremity kinematics were combined with force plate data using an inverse dynamics approach to calculate net moments and powers of the ankles, knees, and hips. Kinetic data were normalized to body weight. All data were expressed as 100% of stair ascent cycle. A custom MatLab® program (Mathworks Inc, Natick, MA, USA) was used to extract peak values for each parameter of interest. Peak values were averaged across three stair ascent cycles for statistical analysis.

A Wilcoxon signed-rank test was used to analyze stair ascent index scores between devices. A 2×2 repeated-measures ANOVA (limb $\times$ device) was used to determine limb (prosthetic and intact) and device (conventional and X2[®]) main effects for each stair ascent condition. Estimated marginal means with a Sidak correction were used for post hoc testing when a significant interaction occurred. Two independent t-tests were used to compare the prosthetic and intact limbs while using the X2[®] knee to the individuals without amputation group. After initial analysis, the data were visually inspected to identify trends in activity performance. We noticed a large variation in prosthetic knee angle throughout the stair ascent cycle and therefore determined what factors were associated with the large variation. Pearson correlations were conducted to examine the relationship between knee positioning and muscular demands, which may provide additional insight into the mechanics of stair ascent while using the X2[®] knee. The level of significance was set at *p* values of less than 0.025 for the independent t-tests to correct for two comparisons. For all other statistical tests, the level of significance was set at *p* values of less than 0.05.

Results

Self-selected Stair Ascent Method

While using the conventional prosthetic knee, 10 of 14 participants self-selected a step-to-step strategy, three a skip-step strategy, and one a step-over-step strategy. When using the X2[®] prosthetic knee, two patients self-selected a step-to-step strategy, two a skip-step strategy, and 10 a step-over-step strategy. Stair ascent index scores during the self-selected condition were higher with X2[®] knee use (median: 11; step-over-step with handrail use) than with conventional knee use (median: 5; step-to-step without handrail use) (*p* = 0.005). Two participants were unable to perform step-over-step stair ascent while using their conventional knee and two participants used a mechanical knee as their conventional knee instead of the C-Leg[®]. Due to the limited number of participants who wore a mechanical knee, and to remove the confounding effect of knee type from biomechanical comparisons, only the 10 individuals who used the C-Leg[®] as their conventional knee and were able to ascend stairs in a step-over-step manner using both devices were included in the biomechanical analysis. Of these 10 individuals, six used two handrails, three used one handrail, and one did not use the handrails while using the X2[®] knee during the controlled cadence condition. To eliminate the confounding variable of speed, only the controlled cadence data are presented.

Between-device and Between-limb Comparisons

Participants with transfemoral amputation demonstrated between-limb differences such as reduced prosthetic limb ankle ROM, moment, and power and reduced prosthetic limb knee extensor moment and power while using either device (Fig. 3). Between-limb differences were observed while using the conventional device for knee (*p* < 0.001) and hip flexion (*p* < 0.001) during swing and hip power generation during push-up (*p* = 0.001) but were no longer present while using the X2[®] device. Participants with transfemoral amputation had a mean of 62° (SD, 43°) more prosthetic knee flexion (*p* = 0.001) and 22° (SD, 14°) more prosthetic limb hip flexion during swing (*p* = 0.001) while using the X2[®] knee than while using the conventional knee (Table 2). Additionally, although not resulting in the removal of between-limb differences, prosthetic knee flexion at heel strike was greater and closer in value to the intact limb while using the X2[®] knee than while using the conventional knee (*p* = 0.003).

X2[®] Knee Compared to Individuals Without Amputation

As expected, the passive prosthetic foot/ankle had less ankle ROM and plantarflexion power generation than the foot/ankle of individuals without amputation (*p* < 0.001) (Fig. 3). The intact ankle was more plantarflexed (*p* < 0.001) and had greater power generation at push-up (*p* = 0.001) than the ankle of individuals without amputation. The prosthetic knee was less flexed at heel strike (*p* = 0.002) and exhibited smaller knee extensor moment (*p* < 0.001) and power generation during pull-up (*p* < 0.001) than the knee of individuals without amputation. However, peak prosthetic knee flexion during swing was not different from the individuals without amputation (*p* = 0.179). The prosthetic and intact hips were more flexed throughout the stair ascent cycle and exhibited greater extension power generation during pull-up (prosthetic: *p* = 0.015, intact: *p* < 0.001) and greater flexion power generation during push-up/swing (prosthetic: *p* = 0.001, intact: *p* = 0.001) than the hip of individuals without amputation.

Correlational Analysis

Greater prosthetic limb knee flexion during initial contact while using the X2[®] was positively correlated with both peak prosthetic limb hip power during pull-up (*r* = 0.641, *p* = 0.046) and peak intact ankle power generation during push-up (*r* = 0.681, *p* = 0.030) (Fig. 3). Prosthetic limb knee flexion angle during initial contact ranged from 1° to

Fig. 3 Graphs show the sagittal-plane lower-extremity kinematics and kinetics for both the intact and prosthetic limbs while using both the X2® and conventional devices and compared to individuals

without amputation. CONV = individuals with a conventional prosthetic knee; CONT = individuals without amputation.

65° across patients, while the corresponding peak prosthetic limb hip power during pull-up ranged from 0.4 to 3.8 W/kg and the peak intact ankle power generation during push-up ranged from 0.6 to 8.0 W/kg. Additionally, peak prosthetic knee flexion during swing while using the X2® knee was highly variable (SD, 43°) and positively correlated with peak prosthetic hip power generation during push-up/early swing ($r = 0.993$, $p < 0.001$). Peak prosthetic knee flexion during swing ranged from 5° to 120° between patients and the corresponding peak prosthetic hip power during push-up/early swing ranged from 0.4 to 2.0 W/kg (see Fig. 4).

Discussion

Stair ascent can be difficult for individuals with transfemoral amputation because of the loss of knee function. Most individuals with transfemoral amputation use either a step-to-step or skip-step strategy because it allows the leading intact limb to do the majority of work. A new micro-processor-controlled knee (X2®) uses flexion/extension resistance to allow step-over-step stair ascent. We compared stair ascent strategies and joint mechanics as individuals with transfemoral amputation ascended stairs using their conventional prosthetic knee and the novel X2® device. Most participants self-selected a step-to-step stair

ascent strategy while using their conventional device and a step-over-step strategy while using the X2® device. Participants were more symmetrical while using the X2® than the conventional device to include more similar peak knee and hip flexion during swing and peak hip power generation during push-up when comparing between limbs. Although the X2® resulted in greater prosthetic knee ROM and fewer between-limb differences than the conventional knee, stair ascent gait deviations still persisted compared to individuals without amputation. Peak knee flexion during swing while using the X2® device was the only prosthetic limb measure that was not different from individuals without amputation. Correlational analysis revealed that greater X2® knee flexion during initial contact and swing was associated with greater prosthetic limb hip power during pull-up and push-up/early swing, respectfully.

This study had two primary limitations. First, the strong relationships between knee angle and hip power may have been influenced by handrail use. We subjectively observed that individuals with transfemoral amputation who contacted the stairs with a less flexed knee and used a smaller amount of hip extension power also relied more on the handrails to transition to the next step. Although most participants had their hands near the rails for safety, visual video inspection showed that individuals with less knee flexion at initial contact tended to use both rails during stair ascent and individuals with greater knee flexion and

Table 2. Kinematic and kinetic data at the ankle, knee, and hip during stair ascent at a controlled cadence (80 steps/minute)

Parameter	Control (no amputation)	Patient's intact limb		Patient's prosthetic limb	
		Conventional	X2 [®]	Conventional	X2 [®]
Dorsiflexion maximum-stance (°)*	24.8 ± 2.7	27.3 ± 8.2 [†]	25.5 ± 8.2 [†]	8.2 ± 4.6	7.0 ± 3.5 [‡]
Plantarflexion maximum-stance (°)*	-14.4 ± 2.8	-25.6 ± 4.4 [†]	-27.0 ± 4.7 ^{†,‡}	3.2 ± 3.7	2.6 ± 3.3 [‡]
Dorsiflexion maximum-swing (°)*	19.1 ± 3.2	18.0 ± 8.3 [†]	17.3 ± 7.8 [†]	3.8 ± 3.7	3.6 ± 3.3 [‡]
Plantarflexion moment maximum (Nm/kg)	1.22 ± 0.22	1.40 ± 0.39 [†]	1.19 ± 0.28 [†]	1.05 ± 0.39	0.79 ± 0.19 [‡]
Plantarflexion power generation maximum 1 (W/kg)	0.56 ± 0.26	2.4 ± 1.34 [†]	1.85 ± 0.85 ^{†,‡}	0.01 ± 0.03	0.09 ± 0.08 [‡]
Plantarflexion power generation maximum 2 (W/kg)	2.10 ± 0.36	1.7 ± 0.81 [†]	2.69 ± 2.23 [†]	0.49 ± 0.32	0.31 ± 0.19 [‡]
Knee flexion maximum-initial contact (°)*	65.7 ± 4.0	73.0 ± 7.8 [†]	73.8 ± 6.3 ^{†,‡}	1.6 ± 3.6	32.5 ± 24.4 ^{‡,§}
Knee flexion minimum-midstance (°)*	5.3 ± 5.6	0.83 ± 6.2	3.4 ± 4.8 [†]	-2.0 ± 3.3	-2.5 ± 2.7 [‡]
Knee flexion maximum-swing (°)*	88.4 ± 7.1	89.7 ± 7.9 [†]	93.1 ± 6.1	6.2 ± 2.9	68.2 ± 43.4 [§]
Knee extension moment maximum (Nm/kg)	1.17 ± 0.39	1.7 ± 0.57 [†]	1.56 ± 0.47 [†]	0.00 ± 0.08	0.16 ± 0.15 [‡]
Knee flexion moment maximum (Nm/kg)	-0.35 ± 0.12	-0.77 ± 0.27	-0.65 ± 0.24 [‡]	-0.85 ± 0.29	-0.65 ± 0.24 ^{‡,§}
Knee power generation maximum (W/kg)	2.34 ± 0.87	3.7 ± 1.12 [†]	3.34 ± 0.99 [†]	0.07 ± 0.03	0.20 ± 0.19 [‡]
Hip flexion maximum-initial contact (°)*	56.6 ± 7.4	71.9 ± 6.5 [†]	77.5 ± 6.3 ^{†,‡,§}	53.0 ± 3.5	69.3 ± 11.8 ^{‡,§}
Hip flexion minimum-midstance (°)*	6.3 ± 8.7	26.8 ± 2.8 [†]	29.2 ± 4.9 ^{†,‡}	14.7 ± 4.4	16.7 ± 6.8 [‡]
Hip flexion maximum-swing (°)*	59.3 ± 7.1	74.0 ± 6.0 [†]	80.3 ± 6.6 ^{†,§}	53.8 ± 2.1	75.7 ± 12.7 ^{‡,§}
Hip extension moment maximum (Nm/kg)	0.55 ± 0.21	1.1 ± 0.36 [†]	1.20 ± 0.40 ^{†,‡}	0.83 ± 0.41	1.03 ± 0.34 [‡]
Hip power generation maximum-pull-up (W)	0.77 ± 0.24	1.29 ± 0.48	2.10 ± 0.89 ^{†,§}	1.07 ± 0.66	1.85 ± 1.12 [‡]
Hip power generation maximum-push-up (W)	0.33 ± 0.09	0.92 ± 0.41 [†]	0.85 ± 0.36 [‡]	0.46 ± 0.20	1.12 ± 0.53 ^{‡,§}

Values are expressed as mean ± SD; * positive value = ankle dorsiflexion, knee and hip flexion; negative value = ankle plantarflexion, knee and hip extension; [†]p < 0.05 for between-limb differences within a device; [‡]p < 0.025 for comparison of prosthetic and intact limbs while using the X2[®] to control; [§]p < 0.05 for post hoc test during the comparison of X2[®] and conventional knees.

increased hip extension power only used one railing. The use of handrails is a limitation of the study but is consistent with previous reports that 93% of individuals with transfemoral amputation use them during stair ascent [12]. The reported lower-extremity joint power values recorded in this study are, however, likely indicative of the actual load placed on the joint while climbing stairs in a real-world environment. Second, this study used a sample of active male individuals with transfemoral amputation, and the conclusions of this study may not apply to less active individuals or females. However, due to current military conflicts, a large majority of individuals with transfemoral amputation are active males.

Most studies report that individuals with transfemoral amputation are unable to ascend stairs using a step-over-step strategy [2, 3, 7, 16]. Similar to previous findings [7, 8], individuals with transfemoral amputation using their conventional knee had a median stair ascent index score of 5 (step-to-step strategy without railing use). However, while using the X2[®] knee, individuals with transfemoral amputation had a median stair ascent index score of 11 (step-over-step strategy with railing use). This finding is consistent with a previous article indicating that individuals self-select a step-over-step stair ascent strategy if provided

a device that provides sufficient support during early stance to prevent collapse of the knee [4]. Using the X2[®] knee, 10 of 14 participants self-selected a step-over-step strategy in contrast to one participant self-selecting this strategy while using his conventional knee.

While using the X2[®] knee, individuals with transfemoral amputation had greater prosthetic knee ROM throughout the gait cycle. Peak values for lower-extremity kinematics with the X2[®] knee were similar to those previously reported with civilians using a comparable prosthetic knee called the Genium[®] [4, 5]. On average, participants had 30° more knee flexion at initial contact and 60° more knee flexion during swing while using the X2[®] device than while using a conventional microprocessor-controlled knee. Despite increased knee flexion at initial contact, between-limb differences were still observed. Although between-limb differences were not observed for peak knee flexion during swing, it may have been the result of high intersubject variability while wearing the X2[®] knee. Peak knee flexion ranged from 1° to 65° at initial contact and 5° to 120° during swing. High intersubject variability may be the result of some participants relying on the X2[®]'s flexion/extension resistance to hold their body weight without collapsing, while other participants adopted

Fig. 4A–D (A) A graph shows the correlation between prosthetic limb hip power during pull-up and prosthetic knee angle at initial contact (IC) while using the X2[®] knee. (B) A graph shows the correlation between prosthetic limb hip power during pull-up and prosthetic knee angle during swing while using the X2[®] knee. (C) A graph shows prosthetic knee angle expressed as 100% gait cycle while using the X2[®] knee for each individual participant. The * symbol

denotes prosthetic knee angle at initial contact and the # symbol denotes prosthetic knee angle during swing. (D) A graph shows prosthetic limb hip power expressed as 100% gait cycle while using the X2[®] knee for each individual patient. The ^ symbol denotes prosthetic limb hip power during pull-up and the + symbol denotes prosthetic limb hip power during push-up.

a more cautious strategy with limited knee flexion and greater use of their arms. As a result of increased knee flexion during swing while using the X2[®] knee, peak hip flexion during swing was also increased and between-limb differences were no longer observed. Increased hip flexion during swing resulted in a stair ascent strategy characterized by increased bilateral hip ROM compared to individuals without amputation. Increased swing hip flexion was likely a compensatory strategy to clear the intermediate stair while using a stair ascent strategy that uses knee flexion instead of hip circumduction.

While using either device, decreased peak prosthetic ankle plantarflexion power at push-up and decreased peak prosthetic knee extension power during pull-up were observed relative to the intact limb and individuals without amputation due to the inability of the prosthetic ankle and knee to generate power. Similar to previous studies examining other microprocessor-controlled knees [4, 5], peak intact ankle plantarflexion power was greater than the passive prosthetic ankle and much larger than the ankle of

individuals without amputation. This large intact ankle power generation observed in individuals with transfemoral amputation is likely used to elevate the body while transitioning from the trailing intact limb to the leading prosthetic limb [19] and a compensation for the inability of the prosthetic knee to produce positive power during pull-up.

Increased initial contact and swing knee flexion while using the X2[®] knee were positively correlated with peak prosthetic limb hip power generation and peak intact ankle power generation. Unlike Bellmann et al. [4, 5], we observed greater prosthetic limb hip extension power during pull-up than individuals without amputation. However, we also observed greater between-subject variability in both prosthetic limb hip extension power during pull-up and knee flexion angle at initial contact. Similar to the work of Bellmann et al. [4, 5], participants in this study that contacted the stair in 35° to 40° of prosthetic knee flexion while using the X2[®] knee used a similar amount of hip power to extend the knee as individuals without

amputation. However, when our participants contacted the stair with a prosthetic knee flexion angle similar to individuals without amputation (approximately 65°), they used approximately five times more hip power to extend the knee than individuals without amputation. Similarly, greater prosthetic limb peak hip power generation was used to initiate prosthetic knee flexion during swing and increased as knee flexion angle increased. These results appear to suggest that individuals with transfemoral amputation must use an adapted strategy that limits prosthetic knee flexion at initial contact and during swing to reduce the power demands placed on the intact joints during step-over-step stair ascent.

Future studies should examine factors, such as device training and hip strength, which may affect an individual's choice of stair ascent strategy while using the X2[®] knee. Furthermore, instrumented railings would allow the objective assessment of the relationship between railing use and hip power generation during pull-up. Additionally, due to the limited number of participants in this study that used a mechanical knee as their conventional knee, we were unable to make biomechanical comparisons between mechanical knees and the X2[®] knee. Future research should examine the biomechanical differences in stair ascent strategy between a mechanical knee and a microprocessor knee, such as the X2[®], that provides extension and flexion resistance.

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