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The relationship of hip strength to walking and balance performance in unilateral lower limb prosthesis users differs by amputation level

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Abstract

Background: Safe and efficient locomotion is a frequently stated goal of lower limb prosthesis users, for which hip strength may play a central yet poorly understood role. Additional research to identify associations between hip strength, balance, and mobility among transtibial and transfemoral prosthesis users is required.

Objective: To test whether residual and/or intact limb isometric hip strength was associated with lower limb prosthesis users' walking speed, endurance, and balance.

Design: Cross-sectional study.

Setting: Research laboratory.

Participants: Convivence sample of 14 transtibial and 14 transfemoral prosthesis users.

Methods: Multiple linear regression was used to evaluate the relationship between isometric measures of residual and intact limb hip strength and walking and balance performance.

Main Outcome Measurements: Measures of isometric hip muscle strength, including peak torque, average torque, torque impulse, and torque steadiness (i.e. consistency with which an isometric torque can be sustained) were derived from maximum voluntary hip flexion, extension, abduction and adduction torque signals collected with a motor-driven dynamometer. Walking speed, endurance, and balance were assessed by administering the 10-meter walk test, 2-minute walk test, Four Square Step Test, and Narrowing Beam Walking Test, respectively.

Results: Residual limb hip extensor max torque and abductor torque steadiness explained between 51% and 69% of the variance in transtibial prosthesis users' walking speed, endurance, and balance. In contrast, intact limb hip abductor torque impulse explained between 33% and 48% of the variance in transfemoral prosthesis users' walking speed, endurance, and balance.

Conclusions: Our results suggest that unilateral transtibial and transfemoral prosthesis users' walking and balance performance may depend on different hip muscles, and different facets of hip strength. Amputation level-specific hip strength interventions may therefore be required to improve walking and balance performance in unilateral transtibial and transfemoral prosthesis users. The "intact leg strategy" adopted by transfemoral prosthesis users may be due

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to a variety of prosthesis and biomechanical factors that limit the efficiency with which transfemoral prosthesis users can exploit the strength of their residual limb hip muscles while walking.

INTRODUCTION

Safe and efficient locomotion is a frequently stated goal of lower limb prosthesis (LLP) users and should, therefore, be a priority during rehabilitation.[1] There is growing evidence that hip strength may play a key role in the safety and efficiency with which LLP users walk.[2] Residual limb hip extensor and/or abductor weakness in LLP users has been associated with reduced walking speed,[3,4] distance,[5] and physical activity levels,[6] as well as increased metabolic cost.[7,8] Despite evidence of intact limb hip compensations,[9,10] much of the research to date has focused on residual limb hip strength of LLP users,[3,5,11] limiting our understanding of any relationship between intact limb hip strength and mobility in LLP users.[2] Furthermore, most studies have concentrated on transtibial prosthesis users[4,6] or merged samples of transtibial and transfemoral prosthesis users,[3,5] thereby impeding our ability to identify amputation level specific associations between hip strength and mobility. The relationship between hip strength and balance also remains understudied[12] and poorly understood.[2] There are currently no data regarding the relationship between the hip strength of LLP users and their balance performance.[13] Additional research to identify associations between hip strength, balance, and mobility among transtibial and transfemoral prosthesis users is required to guide walking- and balance- related assessments, as well as the prescription of existing and development of new rehabilitation strategies intended to increase the safety and efficiency with which LLP users walk. Rehabilitation strategies focused on strength would address one of the top physical health priorities of LLP users.[14]

The primary objective of this study was to test whether residual and/or intact limb isometric hip strength was associated with walking speed, endurance, and balance in individuals using unilateral transtibial and transfemoral prostheses. Based on prior research[3–5,11] we hypothesized that isometric residual limb hip extensor strength would explain a significant proportion of the variance in walking speed and endurance in LLP users, while residual limb hip abductor strength would explain a significant proportion of the variance in their balance performance. To test these hypotheses, secondary questions regarding the dimensionality of isometric hip strength among LLP users were examined with the goal of identifying a set of unrelated measures capable of characterizing the isometric strength of each leg/hip muscle group combination. In doing so we sought to avoid redundancy when attempting to identify the contributions of hip strength to walking and balance performance among LLP users.

MATERIALS AND METHODS

Study Design

A cross-sectional study was conducted to evaluate the association between unilateral LLP users' isometric hip strength and their walking and balance performance. Study procedures were reviewed and approved by an institutional review board at The University of Illinois Chicago. All individuals provided written informed consent prior to participation.

Participant Recruitment

Unilateral transtibial and transfemoral prosthesis users were recruited from a research database managed by the lead author (A.S.). Inclusion criteria were an amputation between the ankle and knee or the knee and hip, a history of wearing a prosthesis for at least 2 years post amputation, the ability to ambulate short distances without an assistive device, 18 years of age or older, and a reported ability to speak and read English. Exclusion criteria included a second amputation, a congenital amputation, or contralateral complications.

Data Collection

Participant characterization

Amputation characteristics, age, gender, history of falls in the past year, and Medicare Functional Classification Level (MFCL) (i.e., K-level) were collected via interview with a study team member who is a certified prosthetist. Perceived mobility was assessed using the Prosthetic Limb Users Survey of Mobility (PLUS-M),[15] whereas balance confidence was assessed using the 5-point scale version of the Activities-specific Balance Confidence (ABC) scale.[16] Socket comfort was evaluated using the Socket Comfort Score (SCS),[17] and participants' body mass, height, and thigh lengths were measured and recorded by a study team member. Residual limb length in individuals with a transfemoral prosthesis was measured from the ischial tuberosity to the distal end of the residual limb while they were wearing their gel liner.

Walking and balance performance

The 10-meter Walk Test (10mWT),[18] 2-Minute Walk Test (2-MWT),[19] Narrowing Beam Walking Test (NBWT),[20] and Four Square Step Test (FSST)[21] were administered to measure participants' walking speed, endurance, and balance. Each test was selected due to evidence of validity[20,22] and reliability[23,24] among LLP users and was administered and scored according to developers' instructions. The 10mWT was performed on level ground over a 14-m walkway, whereas the 2-MWT was performed on level ground over a 20-m walkway.

Isometric hip torque

Maximum voluntary isometric hip flexion, extension, adduction, and abduction torques were recorded with a motor-driven dynamometer (Biodex System 4 Pro, Biodex Medical Systems, Inc., Shirley, NY).[25] Isometric muscle actions were selected due to the relative ease with which they can be performed, their use in previous LLP research,[2] and correlation with isokinetic muscle actions.[26] The prosthesis was removed when testing the residual limb.[27] Flexion and extension torques were collected with participants in a supine position[27] and their hip flexed to 20 degrees.[4] Adduction and abduction torques were collected with participants positioned in a side-lying position and their hip abducted 10 degrees.[28] Participants completed three submaximal practice trials,[29] followed by 15, 5-second maximum voluntary effort trials for each muscle group and leg combination. Ten seconds of rest was given between trials. Participants were instructed to "*push as hard as you can when you hear 'go' and hold that effort until you hear 'relax'*." Verbal encouragement was given during each 5-second trial. Five-minute rest breaks were enforced between each muscle group. The analog signal from the dynamometer was sampled at 1000 Hz and saved for analysis.

Data processing, analysis, and interpretation

Hip torque data processing

The digitized analog signal (NI USB-6341, National Instruments, Austin, TX) was adjusted for the effects of gravity, and smoothed with a zero-order derivative Savitzky–Golay filter.[30] Hip strength was quantified by evaluating two constructs; "how much" torque LLP users' hip muscle groups could produce, and "how consistently" isometric torque could be maintained by those same hip muscle groups. Peak torque, average max torque, and torque impulse were calculated from the processed torque signal to evaluate "how much" torque could be produced. Peak torque was calculated as the maximum torque between signal onset and offset over all 15 trials; average max torque was calculated as the mean of the "plateau," or hold phase, of each trial; torque impulse was calculated as the area under the torque-time curve between signal onset and offset. Torque steadiness (i.e., the ability to sustain a consistent torque level) was calculated as the coefficient-of-variation during the hold phase of each trial.[31] All data processing steps were performed using custom MATLAB (MathWorks, Natick, MA) routines. Measures of hip strength were then adjusted for body size (i.e., body mass $\times$ thigh length) using allometric scaling,[32] rendering them suitable for comparison between people and legs that differ in size.[32] Allometric scaling procedures were conducted using SPSS v.28 (IBM, Chicago, IL).

Statistical analysis

Descriptive analysis
Outliers in the data set were identified and removed if they exceeded a threshold of 2.5 median absolute deviations above or below the median.[33] Departures from normality among continuous variables were assessed with Shapiro–Wilks tests. Continuous and categorical characteristics of the study sample were described using measures of central tendency and dispersion, or frequency and proportion, respectively.

Group differences in hip strength, walking, and balance performance
Mann–Whitney *U* tests or independent-samples *t*-tests were conducted to determine if there were differences in participant characteristics between transtibial and transfemoral prosthesis users. Hotelling's multivariate T^2 tests were conducted to determine if intact or residual limb hip strength and walking or balance performance were significantly different between transtibial and transfemoral prosthesis users. Significant Hotelling's T^2 results were examined with post hoc independent-samples *t*-tests. Hotelling's T^2 tests were chosen because each of the dependent variables (e.g., measures of hip strength or walking and balance performance) had a theoretical basis for being analyzed together. In addition, unlike separate univariate tests, Hotelling's T^2 tests incorporate all comparisons, maintaining a type I error rate of 0.05, and thus greater power of the test of group mean differences, while also considering the relationship (i.e., covariance) between multiple dependent variables.[34]

Redundancy among measures of LLP users' isometric hip strength
Candidate explanatory hip strength variables were identified with a two-step data-reduction process. First, Pearson's correlation tests were conducted between all hip strength variables to identify potential patterns of

collinearity. Correlation magnitude was interpreted using Munro's correlational descriptors (very high = 0.90–1.0, high = 0.70–0.89, moderate = 0.50–0.69, and low 0.26–0.49).[35] When the correlation between two hip strength variables was greater than or equal to 0.70, the measures were considered redundant, and the one with the lower correlation to other measures of hip strength was retained.[35] Through this process a reduced set of unrelated measures capable of characterizing the isometric strength of each leg/hip muscle group combination was created. Next, correlation matrices were constructed between the reduced set of hip strength variables and walking and balance performance. Hip strength variables that were at least moderately correlated with walking or balance performance (i.e., $r \geq 0.50$ and $p < .05$) were carried forward to the multivariable analysis as *candidate explanatory hip strength variables*.[36]

Isometric hip strength contributions to LLP users' walking and balance performance

Multiple linear regression was performed to test whether intact and/or residual limb hip strength explained a proportion of the variance in transtibial and transfemoral prosthesis users' walking and balance performance. Separate models were developed for transtibial and transfemoral prosthesis users' walking speed (10mWT), walking endurance (2-MWT), medial-lateral balance control (NBWT), and multi-directional balance control (FSST). In a bi-directional iterative stepwise procedure, *candidate explanatory hip strength variables* were entered into each regression model at a significance level of $p < .05$ and removed at $p > .10$.

RESULTS

Participant Characteristics

Fourteen unilateral transtibial and 14 unilateral transfemoral prosthesis users participated in the study. Scaled hip torque values in one transfemoral and one transtibial prosthesis user were found to be below the outlier threshold of 2.5 median absolute deviations. Post-testing of both participants confirmed that they did not provide maximum effort consistent with instructions. Both were, therefore, excluded from further analyses, leaving 13 transtibial (8 male/5 female) and 13 transfemoral (6 male/7 female) prosthesis users. The cause of amputation was non-dysvascular in 10 (77%) of the transtibial and 9 (69%) of the transfemoral prosthesis users. Ten (77%) of the transtibial and seven (54%) of the transfemoral prosthesis users had a K3 MFCL, whereas the remainder were K2. All transfemoral prosthesis users wore microprocessor knees. Twenty-three of the 26 participants wore non-articulating energy storage and return feet, and the remaining 3 participants wore a multiaxial foot. Additional characteristics, grouped by level of amputation, are presented in Table 1. Time since amputation and the number of falls in the past 12 months were non-normally distributed (transtibial: $W \leq 0.853$, $p \leq .031$; transfemoral: $W \leq 0.863$, $p < .042$), whereas age, ABC scale scores, PLUS-M T-scores, body mass, height, and thigh length were normally distributed in each group (transtibial: $W \geq 0.879$, $p \geq .069$; transfemoral: $W \geq 0.873$, $p \geq .052$) (Table 1). Pearson chi-square tests and Fisher's exact tests revealed no statistically significant differences in etiology, gender, or MFCL between transtibial and transfemoral prosthesis users ($X^2(1) \leq 1.53$, $p \geq .411$). Mann–Whitney *U* tests revealed no statistically significant differences in body mass, height, age, time since amputation, socket comfort, balance confidence, history of falls, or perceived mobility between the two groups ($U \geq 47.5$, $z \geq -1.90$, $p \geq .057$) (Table 1).

Group differences in walking and balance performance

Except for the FSST (transtibial: $W = 831$ $p = .016$; transfemoral: $W = 794$ $p = .006$), scores on all walking and balance tests were normally distributed in transtibial and transfemoral prosthesis users (transtibial: $W \geq 0.918$; $p \geq .235$; transfemoral: $W \geq 0.879$; $p \geq .069$), (Table 2). Hotelling's T^2 test revealed no statistically significant differences between transtibial and transfemoral prosthesis users' walking and balance scores ($F[6, 19] = 1.27$, $p = .315$, Wilks Lambda = 0.713, partial $\eta^2 = 0.287$), (Table 2).

Group differences in isometric hip strength

In both the residual and intact limb, all measures of isometric hip strength (except for torque steadiness) had statistically significant non-linear associations with body size (mass × thigh length), indicating a confounding effect of body size on strength (Material S1). Allometric scaling[37] was applied and found to remove all observed associations with body size, creating measures of isometric hip strength suitable for analysis and comparison between individuals, and/or legs that differ in size (Material S1). Except for torque steadiness ($W \leq 0.835$, $p \leq .02$) all scaled metrics of isometric hip strength were normally distributed in both the residual and intact limbs of transtibial and transfemoral prosthesis users ($W \geq 0.873$, $p \geq .057$). Hotelling's T^2 test revealed no statistically significant differences in residual or intact limb isometric hip strength between transtibial and transfemoral prosthesis users (residual limb: $F[16, 9] = 1.64$, $p = .228$, Wilks Lambda = 0.255, partial $\eta^2 = 0.745$; intact limb: $F[16, 9] = 2.17$, $p = .120$, Wilks Lambda = 0.206, partial $\eta^2 = 0.794$) (Table 3).

TABLE 1 Anthropometric, amputation, prosthetic, demographic, balance, and mobility-related characteristics of study participants, grouped by level of amputation.

Level of amputation	Mass (kg)	Height (m)	INT thigh length (m)	RL thigh length (m)	Time since amputation (years)	SCS (0–10)	Age (years)	ABC scale (0–4)	No. of falls in past year	PLUS-M (T-score)
Transtibial prosthesis users										
LLA-01	74.4	1.70	0.42	0.42	19	8	63	2.00	0	49.1
LLA-02	85.3	1.80	0.46	0.46	12	7	32	3.94	0	61.0
LLA-03	103	1.86	0.46	0.46	20	9	69	2.44	1	54.4
LLA-04	65.1	1.69	0.41	0.41	17	8	44	2.94	0	47.7
LLA-05	60.5	1.64	0.41	0.41	9	8	55	3.06	1	55.3
LLA-06	118	1.83	0.45	0.45	5	5	36	3.31	2	55.3
LLA-07	77.6	1.73	0.42	0.42	55	9	59	3.25	1	59.6
LLA-08	90.7	1.68	0.41	0.41	6	9	39	3.19	1	55.3
LLA-09	99.8	1.88	0.46	0.46	34	8	56	3.13	0	53.6
LLA-10	59.4	1.64	0.40	0.40	5	5	54	2.06	3	37.1
LLA-11	61.4	1.72	0.42	0.42	24	8	59	3.25	0	59.6
LLA-12	81.3	1.80	0.46	0.46	46	7	78	2.06	1	49.8
LLA-13	87.7	1.56	0.37	0.37	4	10	44	3.69	0	56.3
Mean (95% CI)	81.7 (22.8)	1.73 (0.11)	0.43 (0.034)	0.43 (0.034)	20 (20)	7.7 (2)	52.9 (16.2)	2.95 (0.76)	0.77 (1.12)	53.4 (7.6)
Median (IQR)	81.3 (32.1)	1.72 (0.16)	0.42 (0.050)	0.42 (0.050)	17 (23)	8.0 (2)	55.0 (19.5)	3.13 (1.03)	1.00 (1.00)	55.3 (7.5)
Transfemoral prosthesis users										
LLA-14	101	1.77	0.43	0.28	5	5	25	3.19	0	54.4
LLA-15	69.5	1.66	0.41	0.21	31	10	53	3.44	2	54.4
LLA-16	133	1.81	0.44	0.35	6	10	73	3.13	2	48.4
LLA-17	102	1.87	0.46	0.27	5	7	64	2.38	2	55.3
LLA-18	83.1	1.78	0.44	0.26	7	4	60	2.44	5	48.2
LLA-19	108	1.76	0.43	0.33	17	7	55	2.75	2	48.5
LLA-20	85.2	1.66	0.41	0.24	12	7	59	2.80	1	46.7
LLA-21	69.4	1.75	0.43	0.21	3	7	21	2.56	0	49.8
LLA-22	80.3	1.68	0.41	0.26	21	5	45	1.88	3	45.2
LLA-23	67.9	1.75	0.43	0.22	38	9	61	4.00	0	61.0
LLA-24	57.6	1.74	0.43	0.28	32	10	51	2.63	0	47.7
LLA-25	75.5	1.67	0.41	0.30	3	8	29	2.13	2	47.1
LLA-26	86.5	1.80	0.44	0.27	6	6	73	2.63	0	49.1
Mean (95% CI)	86.0 (24.7)	1.75 (0.07)	0.43 (0.019)	0.27 (0.052)	14 (15)	7.3 (2.0)	51.5 (20.6)	2.77 (0.68)	1.46 (1.82)	50.4 (5.5)
Median (IQR)	83.0 (32.2)	1.75 (0.12)	0.43 (0.030)	0.27 (0.060)	7 (21)	7.0 (4.0)	55.0 (25.5)	2.63 (0.75)	2.00 (2.00)	48.5 (7.0)
p value	.58[a]	.69[a]	.87[a]	< .001[a]	.31[b]	.60[a]	.81[a]	.22[a]	.26[b]	.06[a]

Abbreviations: ABC, Activities-specific Balance Confidence; CI, confidence interval; INT, intact limb; PLUS-M, Prosthesis Limb User Survey – Mobility; RL, residual limb; SCS, Socket Comfort Score; IQR, interquartile range.
[a]Unpaired *t*-test.
[b]Mann–Whitney *U* test.

Redundancy (i.e., collinearity) among measures of LLP users' isometric hip strength

Measures of isometric hip strength were frequently intercorrelated with each other, suggesting redundancy. Pearson's correlation tests identified patterns of collinearity (i.e., $r \geq 0.70$) between peak torque, average max torque, and torque impulse, but not torque steadiness (Material S2). Consequently, for each leg and hip muscle group combination, torque steadiness and one of peak torque, average max torque, or torque impulse were retained as distinct measures of isometric hip strength for further analysis. Exceptions were: (1) transfemoral prosthesis users' intact limb hip abductors, for which peak torque, torque impulse, and torque steadiness were characterized as distinct (i.e., $r < 0.70$); and (2) transtibial prosthesis users' intact limb hip adductors,

TABLE 2 Walking and balance performance of study participants, grouped by level of amputation.

	10mWT (m/s)	2-MWT (m)	FSST (s)	NBWT (/1.0)
Transtibial prosthesis users				
LLA-01	1.22	91.4	27.3	0.11
LLA-02	1.66	229	5.15	0.83
LLA-03	1.08	107	17.8	0.40
LLA-04	1.75	183	6.37	0.78
LLA-05	1.30	183	5.57	0.75
LLA-06	1.37	138	11.8	0.43
LLA-07	1.60	156	10.1	0.48
LLA-08	1.76	198	6.15	0.68
LLA-09	1.68	221	11.1	0.70
LLA-10	1.31	107	9.89	0.38
LLA-11	1.87	193	6.71	0.60
LLA-12	1.17	91.4	21.5	0.08
LLA-13	1.36	122	9.20	0.55
Mean (95% CI lower limit, upper limit)	1.47 (1.31,1.63)	155 (126, 185)	11.4 (7.33, 15.5)	0.52 (0.38, 0.66)
Median (quartile 1, quartile 3)	1.37 (1.26, 1.72)	156 (107, 195)	9.89 (6.26, 14.8)	0.55 (0.39, 0.73)
Transfemoral prosthesis users				
LLA-14	1.29	122	8.47	0.34
LLA-15	1.36	167	8.07	0.70
LLA-16	1.26	91.4	35.3	0.05
LLA-17	1.14	91.4	14.9	0.27
LLA-18	1.60	168	11.5	0.49
LLA-19	1.31	123	12.9	0.41
LLA-20	1.09	91.4	16.6	0.32
LLA-21	1.33	152	14.1	0.67
LLA-22	1.01	91.4	14.4	0.40
LLA-23	1.24	125	9.33	0.36
LLA-24	1.39	158	9.78	0.37
LLA-25	0.99	104	15.6	0.27
LLA-26	0.99	80.0	23.9	0.16
Mean (95% CI lower limit, upper limit)	1.23 (1.12, 1.34)	120 (101, 140)	13.3 (10.5, 16.1)	0.37 (0.26, 0.48)
Median (quartile 1, quartile 3)	1.26 (1.05,1.35)	122 (91.4, 155)	14.1 (9.44, 15.5)	0.36 (0.27, 0.45)

Abbreviations: 10mWT, 10-Meter Walk Test; 2-MWT, 2-Minute Walk Test; CI, confidence interval; FSST, Four Square Step Test; NBWT, Narrowing Beam Walking Test.

for which average max torque, torque impulse, and torque steadiness were found to be distinct. In both cases, all three measures of isometric hip strength were retained for further analysis (Material S2).

Identification of candidate explanatory hip strength variables

Correlations between the reduced set of isometric hip strength variables and lower limb prosthesis users' walking speed, endurance, and balance ranged from 0.01 to 0.72 (Table 4). Transtibial prosthesis users' walking speed and endurance were generally correlated with measures of "how much" isometric torque residual and intact limb hip muscles could produce (e.g., peak torque and average max torque), whereas their balance was generally correlated with residual and intact limb hip torque steadiness (Table 4). Transfemoral prosthesis users' walking speed, endurance, and balance were correlated almost exclusively with measures of "how much" torque the intact limb hip muscles could produce (Table 4). Measures of isometric hip strength found to be significantly correlated with walking speed, endurance, or balance were carried forward as candidate explanatory hip strength variables used to populate the regression models intended to explain the variance in transtibial and transfemoral prosthesis users' walking and balance performance.

TABLE 3 Isometric hip strength scaled to body size, grouped by level of amputation.

	Transtibial	Transfemoral
	Mean (95% CI)	Mean (95% CI)
Hip extensors		
RL peak torque	25.9 (21.2, 30.6)	25.9 (22.1, 29.6)
RL average torque	24.8 (20.4, 29.2)	23.9 (19.8, 28.2)
RL torque impulse	128 (103, 153)	117 (95.1, 141)
RL torque steadiness[a]	4.09 (2.65, 5.54)	3.79 (2.35, 5.24)
INT peak torque	9.61 (7.88, 11.3)	8.06 (6.81, 9.31)
INT average torque	12.7 (10.1, 15.3)	9.97 (8.35, 11.6)
INT torque impulse	68.1 (54.2, 82.1)	53.1 (43.2, 63.1)
INT torque steadiness[a]	4.55 (2.70, 5.54)	3.57 (2.46, 4.67)
Hip flexors		
RL peak torque	19.1 (14.9, 23.2)	17.3 (13.1, 21.4)
RL average torque	18.9 (14.6, 23.2)	19.8 (14.2, 25.4)
RL torque impulse	89.5 (67.2, 112)	78.7 (61.4, 95.9)
RL torque steadiness[a]	4.19 (2.90, 5.47)	3.67 (2.30, 5.04)
INT peak torque	2.92 (2.27, 3.57)	2.42 (1.97, 2.86)
INT average torque	2.59 (1.97, 3.21)	2.09 (1.65, 2.53)
INT torque impulse	14.3 (10.8, 17.8)	11.9 (9.31, 14.5)
INT torque steadiness[a]	4.68 (3.79, 5.57)	4.78 (3.23, 6.33)
Hip abductors		
RL peak torque	28.1 (22.9, 33.3)	25.3 (20.4, 30.2)
RL average torque	18.7 (15.3, 22.2)	18.6 (13.7, 23.5)
RL torque impulse	91.1 (70.8, 111)	82.2 (64.4, 100)
RL torque steadiness[a]	4.46 (2.98, 5.95)	3.99 (2.56, 5.42)
INT peak torque	2.59 (2.13, 3.05)	2.08 (1.75, 2.41)
INT average torque	11.8 (9.29, 14.3)	9.41 (7.37, 11.5)
INT torque impulse	58.2 (45.7, 70.7)	43.3 (36.1, 50.6)
INT torque steadiness[a]	6.38 (4.01, 8.77)	6.32 (4.27, 8.38)
Hip adductors		
RL peak torque	13.8 (11.1, 16.5)	13.9 (11.7, 16.2)
RL average torque	8.99 (7.14, 10.8)	9.73 (7.90, 11.6)
RL torque impulse	62.5 (51.5, 73.4)	60.8 (48.3, 73.3)
RL torque steadiness[a]	3.86 (2.71, 5.02)	3.78 (2.40, 5.16)
INT peak torque	2.51 (2.18, 2.83)	1.71 (1.43, 1.98)
INT average torque	2.21 (1.87, 2.54)	1.50 (1.23, 1.78)
INT torque impulse	55.9 (42.2, 69.6)	39.7 (33.1, 46.3)
INT torque steadiness[a]	5.12 (3.58, 6.75)	4.22 (3.15, 5.29)

Abbreviations: INT, intact limb; RL, residual limb.
[a]Not scaled to body size due to lack of a significant association.

Multivariable associations between isometric hip strength and walking speed, endurance, and balance

A combination of residual limb hip extensor average max torque and residual limb hip abductor torque steadiness explained 69% and 60% of the variance in transtibial prosthesis users' walking speed and endurance, respectively (Table 5). Only residual limb hip abductor torque steadiness was retained in the final balance models, explaining 52% and 51% of the variance in transtibial prosthesis users' multidirectional balance control (i.e., FSST) and medial-lateral balance control (i.e., NBWT), respectively (Table 5). The percentage of variance explained by the specific hip strength metrics in each transtibial model is presented in Table 5. Among transfemoral prosthesis users, only intact limb hip abductor torque impulse was retained, explaining 33% to 48% of the variance in walking speed, endurance, and balance (Table 5). For each of the final models, the variance inflation factor was at or near 1, indicating no multicollinearity, and Durbin-Watson statistics were ≈2.0, indicating an absence of correlation between residuals.

DISCUSSION

The objective of this study was to test whether residual and/or intact limb isometric hip strength was associated with walking speed, endurance, and balance in unilateral transtibial and transfemoral prosthesis users. We hypothesized that greater isometric residual limb hip extension strength would be associated with walking faster and farther, whereas greater residual limb hip abduction strength would be associated with better balance performance. In partial support of our hypothesis, residual limb hip extensor average max torque and abductor torque steadiness explained between 51% and 69% of the variance in transtibial prosthesis users' walking speed, endurance, and balance. In contrast, intact limb hip abductor torque impulse explained a statistically significant but smaller proportion of the variance in transfemoral prosthesis users' walking speed (33%), endurance (46%), and balance (35%–48%). Our results suggest that transtibial and transfemoral prosthesis users' walking and balance ability may depend on different hip muscles, and different facets of hip strength.

Consistent with prior research, residual limb hip extensor strength was found to be the primary hip strength determinant of unilateral transtibial prosthesis users' walking speed and endurance, explaining 51% and 36% of the variance, respectively.[3–5] The consistency and strength of this relationship across the literature regardless of the muscle action studied (i.e., isometric or isokinetic) underscores the importance of transtibial prosthesis users maintaining and/or developing sufficient residual limb hip extensor strength to preserve or improve their walking speed and endurance. Although residual limb hip extensor strength has also been found to be associated with walking speed and endurance in unilateral transfemoral prosthesis users,[3,5]

TABLE 4 Pearson's correlation coefficients between the reduced set of isometric hip strength variables and performance on walking and balance tests, grouped by level of amputation.

	10-Meter Walk Test	2-Minute Walk Test	Four Square Step Test	Narrowing Beam Walking Test
Transtibial prosthesis users				
Hip extensors				
RL average torque	0.72 (0.36, 1.0)[a]	0.60 (0.17, 1.0)[a]	−0.33 (−1.0, 0.17)	0.30 (−0.20, 1.0)
RL torque steadiness	−0.26 (−1.0, 0.25)	−0.091 (−1.0, 0.40)	0.14 (−0.36, 1.0)	−0.07 (−1.0, 0.43)
INT average torque	0.69 (0.32, 1.0)[a]	0.40 (−0.10, 1.0)	−0.29 (−1.0, 0.21)	0.15 (−0.36, 1.0)
INT torque steadiness	−0.32 (−1.0, 0.18)	−0.37 (−1.0, 0.014)	0.57 (0.13, 1.0)[a]	−0.47 (−1.0, 0.0061)
Hip flexors				
RL peak torque	0.43 (−0.062, 1.0)	0.34 (−0.17, 1.0)	−0.46 (−1.0, 0.02)	0.26 (−0.25, 1.0)
RL torque steadiness	−0.57 (−1.0, −0.13)[a]	−0.46 (−1.0, 0.03)	0.49 (0.02, 1.0)[a]	−0.41 (−1.0, 0.083)
INT average torque	0.60 (0.17, 1.0)[a]	0.48 (0.0023, 1.0)[a]	−0.53 (−1.0, −0.077)[a]	0.41 (−0.096, 1.0)
INT torque steadiness	−0.42 (−1.0, 0.072)	−0.50 (−1.0, −0.031)[a]	0.52 (0.054, 1.0)[a]	−0.40 (−1.0, 0.10)
Hip abductors				
RL average torque	0.57 (0.13, 1.0)[a]	0.56 (0.11, 1.0)[a]	−0.41 (−1.0, 0.088)	0.36 (−0.14, 1.0)
RL torque steadiness	−0.52 (−1.0, −0.21)[a]	−0.51 (−1.0, −0.044)[a]	0.72 (0.37, 1.0)[a]	−0.72 (−1.0, −0.36)[a]
INT average torque	0.54 (0.085, 1.0)[a]	0.46 (−0.026, 1.0)	−0.50 (−1.0, −0.032)[a]	0.33 (−0.17, 1.0)
INT torque steadiness	−0.36 (−1.0, 0.15)	−0.47 (−1.0, 0.0057)	0.52 (0.27, 1.0)[a]	−0.70 (−1.0, −0.34)[a]
Hip adductors				
RL peak torque	0.65 (0.25, 1.0)[a]	0.55 (0.094, 1.0)[a]	−0.34 (−1.0, 0.16)	0.35 (−0.16, 1.0)
RL torque steadiness	0.12 (−0.38, 1.0)	−0.08 (−1.0, 0.41)	−0.05 (−1.0, 0.44)	−0.17 (−1.0, 0.33)
INT average torque	0.60 (0.17, 1.0)[a]	0.40 (−0.10, 1.0)	−0.42 (−1.0, 0.078)	0.33 (−0.18, 1.0)
INT torque impulse	0.58 (0.14, 1.0)[a]	0.48 (0.0011 1.0)[a]	−0.31 (−1.0, 0.20)	0.24 (−0.27, 1.0)
INT torque steadiness	−0.22 (−1.0, 0.29)	−0.46 (−1.0, 0.023)	0.53 (0.076, 1.0)[a]	−0.62 (−1.0, −0.20)[a]
Transfemoral prosthesis users				
Hip extensors				
RL peak torque	0.46 (−0.022, 1.0)	0.48 (0.0047, 1.0)[a]	−0.03 (−1.0, 0.46)	0.35 (−0.15, 1.0)
RL torque steadiness	−0.04 (−1.0, 0.45)	−0.05 (−1.0, 0.45)	−0.10 (−1.0, 0.40)	0.23 (−0.28, 1.0)
INT peak torque	0.42 (−0.070, 1.0)	0.48 (0.0031, 1.0)[a]	−0.10 (−1.0, 0.39)	0.20 (−0.30, 1.0)
INT torque steadiness	0.19 (−0.32, 1.0)	0.22 (−0.29, 1.0)	−0.14 (−1.0, 0.36)	0.56 (0.11, 1.0)[a]
Hip flexors				
RL average torque	0.13 (−0.37, 1.0)	−0.06 (−1.0, 0.43)	−0.13 (−1.0, 0.37)	0.11 (−0.39, 1.0)
RL torque steadiness	−0.10 (−1.0, 0.41)	0.09 (−0.41, 1.0)	−0.07 (−1.0, 0.43)	0.44 (−0.055, 1.0)
INT peak torque	0.42 (−0.071, 1.0)	0.54 (0.080, 1.0)[a]	−0.48 (−1.0, 0.011)	0.59 (0.16, 1.0)[a]
INT torque steadiness	0.02 (−0.47, 1.0)	−0.07 (−1.0, 0.43)	0.01 (−0.47, 1.0)	0.24 (−0.27, 1.0)
Hip abductors				
RL average torque	0.32 (−0.19, 1.0)	0.34 (−0.16, 1.0)	−0.23 (−1.0, 0.28)	0.36 (−0.14, 1.0)
RL torque steadiness	0.11 (−0.39, 1.0)	0.12 (−0.38, 1.0)	0.05 (−0.45, 1.0)	0.40 (−0.10, 1.0)
INT peak torque	0.53 (0.089, 1.0)[a]	0.61 (0.19, 1.0)[a]	−0.43 (−1.0, 0.058)	0.63 (0.22, 1.0)[a]
INT torque impulse	0.57 (0.13, 1.0)[a]	0.68 (0.30, 1.0)[a]	−0.72 (−1.0, −0.37)[a]	0.70 (0.33, 1.0)[a]
INT torque steadiness	−0.24 (−1.0, 0.27)	−0.16 (−1.0, 0.34)	0.04 (−0.45, 1.0)	0.30 (−0.21, 1.0)
Hip adductors				
RL peak torque	0.064 (−0.43, 1.0)	0.14 (−0.36, 1.0)	0.04 (−0.48, 1.0)	0.03 (−0.47, 1.0)
RL torque steadiness	0.13 (−0.37, 1.0)	0.10 (−0.40, 1.0)	0.16 (−0.35, 1.0)	0.27 (−0.24, 1.0)
INT peak torque	0.24 (−0.27, 1.0)	0.48 (0.0012, 1.0)[a]	−0.32 (−1.0, 0.19)	0.27 (−0.24, 1.0)
INT torque steadiness	−0.43 (−1.0, 0.07)	−0.41 (−1.0, 0.083)	0.12 (−0.38, 1.0)	0.03 (−0.45, 1.0)

Note: Data are correlation coefficients (95% confidence interval).

[a]Statistically significant correlation. Metric carried forward to model building stage.

TABLE 5 Amount of variance in walking and balance performance explained by isometric hip strength variables in unilateral transtibial ($n = 13$) and transfemoral ($n = 13$) prosthesis users.

Independent variable(s)	β (95% CI)	R^2 change	*t*-statistic (*p* value)	Durbin-Watson	VIF
Transtibial 10mWT model: $F(2,10) = 11.29$, $p = .003$, $R^2 = 0.693$, SEE = 0.158					
Constant (β_0)	1.10 (0.747, 1.46)		6.91 (<.001)	2.06	1.04
RL hip extension average torque	0.045 (0.021, 0.069)	0.511	4.23 (.002)		
RL hip abduction steadiness	−0.045 (−0.087, −0.004)	0.182	−2.44 (.035)		
Transfemoral 10mWT model: $F(1,11) = 5.36$, $p = .041$, $R^2 = 0.327$, SEE = 0.153					
Constant (β_0)	0.857 (0.490, 1.22)		5.14 (<.001)	2.25	1.00
INT hip abduction impulse	0.009 (0.000, 0.017)	0.327	2.31 (.041)		
Transtibial 2-minWT model: $F(2,10) = 7.46$, $p = 0.010$, $R^2 = 0.599$, SEE = 33.9					
Constant (β_0)	101.5 (13.5, 189)		2.57 (.028)	1.62	1.01
RL hip extension average torque	3.93 (0.927, 6.93)	0.360	2.92 (.015)		
RL hip abduction steadiness	−9.76 (−18.7, −0.846)	0.239	−2.44 (.035)		
Transfemoral 2-minWT model: $F(1,11) = 9.51$, $p = 0.010$, $R^2 = 0.464$, SEE = 24.4					
Constant (β_0)	41.6 (−16.5, 99.8)		1.58 (.144)	2.52	1.00
INT hip abduction impulse	1.82 (0.520, 3.11)	0.464	3.08 (.010)		
Transtibial FSST model: $F(1,11) = 11.91$, $p = .005$, $R^2 = .520$, SEE = 4.91					
Constant (β_0)	2.52 (−3.90, 8.95)		0.864 (.406)	2.19	1.01
RL hip abduction steadiness	2.00 (.723, 3.29)	.520	3.45 (.005)		
Transfemoral FSST model: $F(1,11) = 5.43$, $p = .042$, $R^2 = 0.352$, SEE = 3.74					
Constant (β_0)	24.5 (13.5, 35.5)		4.98 (<.001)	1.21	1.00
INT hip abduction impulse	−0.248 (−0.486, −0.011)	0.352	−2.33 (.042)		
Transtibial NBWT model: $F(1,11) = 11.5$, $p = 0.006$, $R^2 = 0.511$, SEE = 3.85					
Constant (β_0)	18.3 (13.3, 23.3)		8.01 (<.001)	1.86	1.01
RL hip abduction steadiness	−1.54 (−2.53, −0.539)	0.511	−3.39 (.006)		
Transfemoral NBWT model: $F(1,11) = 10.27$, $p = 0.008$, $R^2 = 0.483$, SEE = 2.98					
Constant (β_0)	−1.89 (−8.99, 5.21)		−0.587 (.569)	2.08	1.00
INT hip abduction impulse	0.231 (0.0723, 0.389)	0.483	3.21 (.008)		

Abbreviations: 10mWT, 10-Meter Walk Test; 2-minWT, 2-Minute Walk Test; β, standardized beta coefficient; FSST, Four Square Step Test; INT, intact limb; NBWT, Narrowing Beam Walking Test; RL, residual limb; SEE, standard error of the estimate; VIF, variance inflation factor.

a similar relationship was not found in the current study. Consistent with the only other study to assess the relationship between hip strength and walking performance in a standalone sample of transfemoral prosthesis users',[11] we found that although correlated with walking endurance, residual limb hip extensor strength did not explain a significant proportion of the variance in transfemoral prosthesis users' walking endurance or speed. Unlike transtibial prosthesis users, residual limb isometric hip extensor strength does not appear to be a significant determinant of transfemoral prosthesis users' walking speed or endurance. Rather, intact limb hip abductor strength (i.e., torque impulse), was the only isometric measure of hip strength that explained a significant proportion of transfemoral prosthesis users' walking speed (33%) and endurance (46%). The association of intact rather than residual limb hip strength with transfemoral prosthesis users' walking speed and endurance is consistent with prior biomechanical modeling of transfemoral prosthesis users' gait.[9,10] Transtibial and transfemoral prosthesis users' walking speed and endurance appear to depend on different hip muscles. Amputation level–specific interventions that target different hip muscles may be necessary to increase the walking speed and endurance of transtibial and transfemoral prosthesis users.

As with walking speed and endurance, the relationship between hip strength and balance varied with amputation level. Like walking speed and endurance, transfemoral prosthesis users' balance ability was associated with the strength of their intact limb hip abductors (i.e., $R^2 > 0.35$). In contrast, the balance performance of transtibial prosthesis users was associated with residual limb hip abductor torque steadiness (i.e., $R^2 > 0.50$). As we are unaware of any studies that have previously examined the association between hip strength and balance performance in LLP users, the current results represent an initial attempt to establish said relationship both in terms of hip muscle groups and facets of strength. Several previously unexplored clinical and scientifically relevant interpretations may be drawn from these novel results. First, the safety and mobility of transfemoral prosthesis users appear to hinge on the strength of their intact limb hip muscles, whereas transtibial prosthesis users appear to rely on their residual limb hip muscles. Given the weakness of LLP users' intact limb hip muscles relative to their residual limb,[38,39] historical impairments in transfemoral prosthesis users' balance and mobility relative to those of transtibial prosthesis users may be attributed in part to their dependence on the intact leg.[40] Second, measures of hip strength that were associated with the balance performance of transtibial and transfemoral prosthesis users also explained a significant proportion of the variance in their walking speed and endurance. For example, not only did residual limb hip abductor torque steadiness account for more than 50% of the variance in transtibial prosthesis users' balance performance, but it also explained a significant, albeit smaller, proportion of the variance in their walking speed (18%) and endurance (24%). The overlap in hip strength requirements for balance and mobility among transtibial and transfemoral users suggests that the ability to walk faster and farther may depend on having sufficient hip strength to maintain some degree of balance (i.e., balance serves as a foundation for mobility). Although we are not aware of any studies that have examined the relationship between hip torque steadiness and walking or balance performance in LLP users, greater hip abduction torque steadiness has been associated with less postural sway as well as increased walking speed and endurance in healthy adults[41] and adults with multiple sclerosis,[42] respectively. Additional research is needed to quantify torque steadiness across a range of contraction levels and muscle groups in LLP users.

The demands placed on the residual limb hip muscles of transfemoral prosthesis users by prosthesis-related tasks may reduce their capacity to make simultaneous contributions to walking and balance performance. Transfemoral prosthesis users' residual limb hip muscles are thought to be involved in managing several prosthesis-related tasks with which transtibial prosthesis users do not have to contend. These include stabilizing the residual limb within the socket,[43] preventing[44] and decreasing[45] high pressure areas between the socket and pelvis,[42,45,46] and maintaining some control over the prosthetic knee.[46] Due to the added burden placed on their residual limb hip muscles, transfemoral prosthesis users may have to rely on alternative strategies to regulate walking and balance. Consistent with previous biomechanical analyses,[9,10] our results suggest that unlike transtibial prosthesis users, who utilize their residual limb hip muscles to control walking and balance,[47] transfemoral prosthesis users adopt an "intact leg strategy," emphasizing intact limb hip, ankle, and potentially knee[39] muscle contributions to walking and balance. Competition between gait and prosthesis-related tasks for residual limb hip muscle resources in transfemoral prosthesis users may also increase the simultaneous activation of residual limb agonist and antagonist hip muscles.[46] The resulting hip muscle co-contraction may further reduce the contributions of transfemoral prosthesis users' residual limb agonist hip muscles to walking and balance performance. Evidence of residual limb hip muscle co-contraction among transfemoral prosthesis users, and its impact on balance and mobility, however, remains largely anecdotal and untested.[43,46] Although transfemoral and transtibial prosthesis users have been reported in one study to have comparable residual limb hip strength,[32] it would appear that transfemoral prosthesis users are unable to exploit this strength to assist with the control of walking and balance.

Except for amputation etiology, the distribution of demographic, amputation, and activity characteristics of study participants were generally consistent with those in larger national studies of LLP users (i.e., $n = 146$–1568).[48,49] The results of this study may, therefore, generalize to the broader population of established unilateral non-dysvascular transtibial and transfemoral prosthesis users. Future research with larger sample sizes is needed to conduct important sub-group analyses that examine the influence of amputation-related factors, including time since amputation and amputation etiology and other physical factors including hip and lumbar range of motion, as well as age and amputation technique on the association between hip strength, balance, and mobility. The present study was limited to the isometric strength of hip muscle groups. Whether additional muscle groups, different strength metrics, isokinetic muscle actions, or closed-chain muscle strength tests would explain any of the remaining variance, or a greater proportion of the variance in LLP users' walking and balance performance remains to be determined. There is recent evidence, however, that the strength of the intact limb knee extensors,[38,48,50] and rate-based measures such as power[3] derived from isokinetic rather than isometric muscle actions, may also be associated with walking and balance performance in LLP users. Measures of isometric hip torque impulse and steadiness were obtained using a motor-driven dynamometer. In clinical settings where access to a motor-driven dynamometer is not possible, such assessments may be challenging. One alternative for clinicians may be to characterize key hip strength variables including torque impulse and steadiness with a handheld dynamometer. Prior to clinical implementation, additional research is, however, required to evaluate the validity and reliability[6] of hip strength measures obtained from LLP users with a handheld dynamometer. Walking speed, endurance, and balance were assessed using performance-based clinical tests with evidence of validity[20,22] and reliability[23,24] in LLP users. Although these methods provide ease of administration, they may not reflect the gold standard for quantifying walking endurance (e.g., indirect calorimetry) and balance (e.g., falls). Future research should build upon the current results by testing whether hip strength is associated with laboratory and community-based gold standard assessments of walking endurance and balance. Finally, because the current models were developed using a stepwise data-driven approach rather than a priori determination of the predictive variables, R^2 estimates may be optimistic.[51] Additional research is required, therefore, to determine whether the proposed models are valid beyond the current sample.

CONCLUSION

Our results indicate that the walking and balance performance of unilateral non-dysvascular transtibial and transfemoral prosthesis users depends on the strength of different hip muscles. Although the walking speed, endurance, and balance of transtibial prosthesis users appear to be associated with the strength of their residual limb hip extensor and abductor muscles, the same mobility and safety outcomes in transfemoral prosthesis users depend on the strength of their intact limb hip abductors alone. We attribute this "intact leg strategy" adopted by transfemoral prosthesis users to a host of prosthesis and biomechanical factors that act to limit the efficiency with which transfemoral prosthesis users can exploit the strength of their residual limb hip muscles while walking. Although additional research examining the contributions of non-hip muscle groups to walking and balance performance in LLP users is needed, our results indicate that amputation level–specific hip strength interventions may be required to improve the walking and balance performance of LLP users.

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DISCLOSURES

The authors declare no competing interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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