



Understanding lower limb muscle volume adaptations to amputation

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ABSTRACT

Amputation of a major limb, and the subsequent return to movement with a prosthesis, requires the development of compensatory strategies to account for the loss. Such strategies, over time, lead to regional muscle atrophy and hypertrophy through chronic under or overuse of muscles compared to uninjured individuals. The aim of this study was to quantify the lower limb muscle parameters of persons with transtibial and transfemoral amputations using high resolution MRI to ascertain muscle volume and to determine regression equations for predicting muscle volume using femur- and tibia-length, pelvic-width, height, and mass. Twelve persons with limb loss participated in this study and their data were compared to six matched control subjects. Subjects with unilateral transtibial amputation showed whole-limb muscle volume loss in the residual-limb, whereas minor volume changes in the intact limb were found, providing evidence for a compensation strategy that is dominated by the intact-limb. Subjects with bilateral-transfemoral amputations showed significant muscle volume increases in the short adductor muscles with an insertion not affected by the amputation, the hip flexors, and the *gluteus medius*, and significant volume decreases in the longer adductor muscles, *rectus femoris*, and hamstrings.

This study presents a benchmark measure of muscle volume discrepancies in persons with limb-loss, and can be used to understand the compensation strategies of persons with limb-loss and the impact on muscle volume, thus enabling the development of optimised intervention protocols, conditioning therapies, surgical techniques, and prosthetic devices that promote and enhance functional capability within the population of persons with limb loss.

1. Introduction

Traumatic lower-limb amputation results in changes to movement biomechanics through immediate disruption to neuromusculoskeletal body systems (Geurts and Mulder 1992, Silverman et al. 2008, Clites et al. 2018). Returning to movement using a prosthesis requires the development of new motor control strategies. Chronic increase or decrease in muscle activity results in hypertrophy or atrophy of muscle volume (V_m ; Edgerton et al. 2002, Phillipset al. 2009) and a resulting change in maximum muscle force (F_{MAX}). In persons with unilateral amputation, muscular disuse atrophy is seen in the muscles of the amputated-limb compared to the non-amputated-limb (Renström et al. 1983, Jaegers et al. 1995, Burger et al. 1996, Schmalz et al. 2001). This

is evidence of a compensatory strategy that favours the intact-limb over the residual, demonstrated by decreased ground reaction force, power, and moment production in the residual-limb compared to the intact-limb in gait analysis studies (Winter and Sienko 1988, Norvell et al. 2005, Ding et al. 2020). It follows that muscles that have increased recruitment because of the compensation strategy employed will exhibit hypertrophy. In an uninjured population, the main determinant of F_{MAX} is muscle size (Haxton 1944, Erskine et al. 2009). However, in atrophic or hypertrophic muscles, the percentage change in measured F_{MAX} is disproportionate to the percentage change in muscle size (Narici and Cerretelli 1998, Erskine et al. 2010) due to changes to muscle characteristics including fibre length, pennation angle, muscle composition, and levels of voluntary muscle activation (Morrison et al. 1987, Grassi

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et al. 1991, Buchanan 1995, Edgerton et al. 2002, Boonyarom and Inui 2006, Sibley et al. 2020). Therefore, understanding a muscle's physiological atrophic or hypertrophic state is essential for developing accurate representations of F_{MAX} .

High-resolution magnetic resonance imaging (MRI) can be used to accurately reproduce anatomical geometry (Smith et al. 1989, Albracht et al. 2008). However, using MRI has a high resource demand, often proving prohibitive. Using readily measurable subject parameters from persons with limb-loss (PWLL; e.g., femur-length, tibia-length, pelvic-width) in addition to subject mass and height (Handsfield et al. 2014, Maden-Wilkinson et al. 2014) to identify relationships to V_m would be beneficial for improving PWLL model accuracy.

The objective of this study was to quantify V_m of lower-limb muscles of persons with amputations. Secondly, this study explored the relationships between different anthropometric measures and V_m in the PWLL population. Finally, this study characterised patterns of V_m changes among PWLL through comparison to literature detailing PWLL kinetics and kinematics.

2. Methods

2.1. Subjects

This study compared the muscle volumes of PWLL with control subjects (CS) using high-resolution MRI scans that enable digital reconstruction of anatomical structures. Six persons with bilateral amputations at either the transfemoral or knee-disarticulation levels (classified as bilateral-transfemoral, BTF) and six persons with unilateral-transfemoral amputations (UTT) were recruited for this study. All PWLL subjects were male, military veterans, and had undertaken extensive rehabilitation therapy. The subjects all ambulated freely (i.e., K4; Gailey et al. 2002) without the use of additional assistive products. BTF height was determined from military records. PWLL subject mass is inclusive of prosthetic(s). All UTT used a form of dynamic-response foot, and some included multi-axis ankles. All BTF used high-specification microprocessor knee joints in combination with dynamic-response

feet. Data from both limbs (to cater for interlimb muscle variations) of six male CS without limb-loss were matched for height, mass, and age from a pool of datasets (Ding et al. 2019). Subject data are presented in Table 1. The study protocols were approved by the Imperial College Research Ethics Committee (Reference 16IC3562) and NHS REC (reference 16/LO/1715). Written informed consent to take part in this study was obtained from all participants.

2.2. Data acquisition and processing

A 3 T MRI scanner (MAGNETOM Verio, Siemens, Germany) was used to collect MRI data with a 3D T1-weight spoiled gradient echo sequence (Siemens VIBE) with imaging field-of-view 450x450mm, an axial-plane resolution 1.17x1.17 mm, slice thickness 1 mm, from iliac crest to the most distal point on the longest lower-limb. The 2D contours of each muscle and bone were developed from the MRI using Mimics (Mimics 19.0, Materialise, Belgium). These 2D contours (Fig. 1a) were stacked and compiled in 3D to deliver V_m (Fig. 1b). Muscle belly length (L_m) was determined first by identifying the final axial slices in the superior and inferior directions with clearly identifiable muscle tissue for each muscle. The spline function in Mimics was then used to follow the central muscle-axis between these two points, and spline length was used as L_m (Fig. 1c). An intra-user error of 1.79% was determined through manual segmentation of the same muscle four times, which is slightly higher than the error reported for segmentation of simple phantom shapes (<0.5%; Handsfield et al. 2014) but less than that for complex shapes (<3%; Ward et al. 2009). As the psoas has a superior origin at above the superior cut-off of the study MRI protocol, the psoas V_m was determined from the axial slice containing the most superior element of the iliac crest to the distal insertion and combined with the Iliacus muscle volume to present a combined iliopsoas volume.

Femur-length was measured from the most lateral aspect of the greater trochanter to the most lateral aspect of the lateral femoral condyle to represent measures obtainable without imaging facilities. In BTF subjects with an incomplete femur, the length was measured from the most lateral aspect of the greater trochanter to the most distal point

Table 1
Subject datasheet.

Subject	Age (yrs)	Height (pre-injury) (cm)	Mass (kg)	Time Since Amp. (yrs)	Femur Length (GT to LC - cm)		Tibia Length (cm)	Pelvic Width (cm)	Total Limb Muscle Volume (cm ³)	
					L	R			L	R
CS1	32	174	78	–	40.3	39.6	–	21.2	8296.6	8118.8
CS2	34	176	108	–	39.2	38.2	–	24.2	7813.8	7723.0
CS3	31	185	93	–	43.8	43.7	–	21.9	9883.4	9519.1
CS4	43	183	96	–	40.3	40.0	–	22.6	9259.8	9285.5
CS5	28	192	85	–	43.2	43.2	–	24.0	9122.3	11058.2
CS6	36	172	70	–	38.1	38.1	–	23.6	7816.0	7624.0
Group Mean	34.0	180.3(7.7)	88.3	–	40.8	40.5	–	22.9(1.1)	8698.7	8888.1
(SD)	(5.2)		(13.6)		(2.3)	(2.4)			(851.1)	(1327.6)
					Intact	Amp	Amp		Intact	Amp
UTT1	32	182	98	6	40.6	41.3	12.1	26.5	9579.75	6152.9
UTT2	32	176	76.7	6	38.9	38.8	14.9	22.3	7705.188	6255.9
UTT3	37	185	94.3	8	38.6	38.6	12.3	24.5	8839.79	6659.3
UTT4	34	177	79.2	8	40.3	40.6	13.3	21.1	6834.202	5101.7
UTT5	34	181	81.4	8	39.6	39.4	14.4	24.6	6795.986	5574.1
UTT6	33	180	101.6	9	38.8	39.4	14.2	22.9	9711.269	7312.0
Group Mean	33.7	180.2(3.3)	88.5	7.5	39.5	39.9	13.5(1.1)	23.7(1.9)	8244.4	6176.0
(SD)	(1.9)		(10.7)		(0.8)	(1.1)			(1316.6)	(780.7)
					L	R			L	R
BTF1	32	185	86	6	41.9	35.0	–	23.13	6945.7	5987.5
BTF2	27	178	81.2	6	28.0	36.3	–	23.89	4443.2	5052.5
BTF3	36	186	90	7	41.4	28.9	–	24.66	6395.9	5797.9
BTF4	33	182	89.5	9	39.9	39.3	–	22.74	5466.1	5541.8
BTF5	32	185	97.2	8	41.8	41.5	–	24.06	6189.1	6248.6
BTF6	31	171	68.8	7	28.8	29.5	–	20.57	4217.7	4379.4
Group Mean	31.8	181.2(5.8)	85.5(9.7)	7.2	35.1	37.0	–	23.2(1.4)	5609.6	5501.3
(SD)	(2.9)				(5.1)	(6.7)			(1100.7)	(684.7)

GT – greater trochanter, LC – lateral condyle, CS – control subject, UTT – unilateral transtibial, BTF – bilateral transfemoral, L – left, R – right

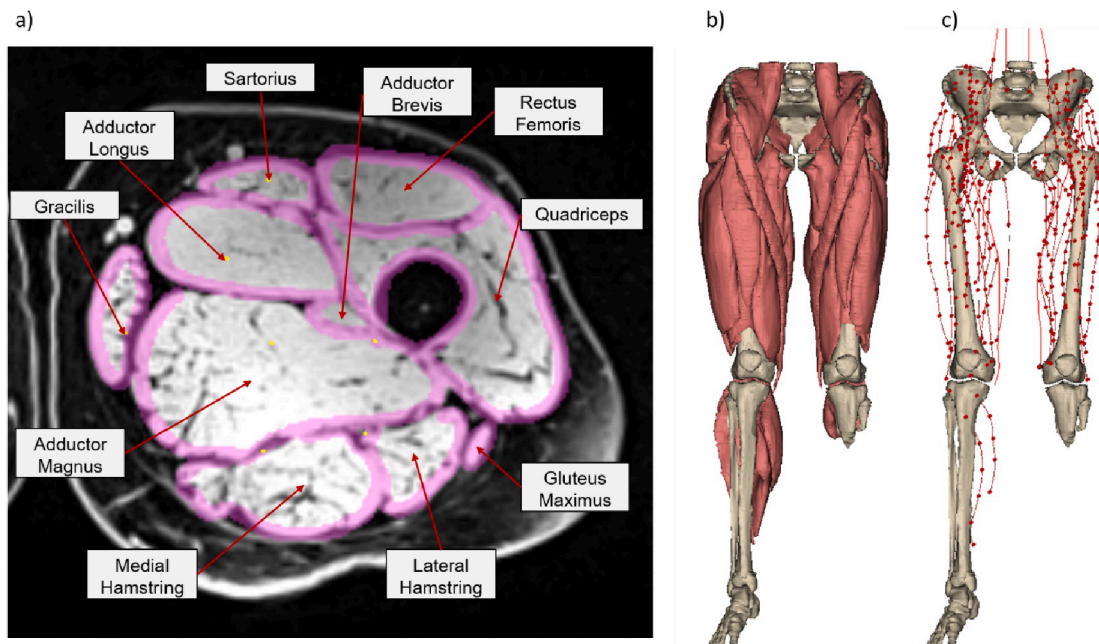


Fig. 1. Reconstruction of anatomical architecture from (a) 2D muscle contouring to (b) 3D muscle reconstruction and (c) spline function determination of muscle belly lengths in a representative UTT subject.

of the femur. Pelvic-width was measured as the distance between the anterior superior iliac spines. Tibia-length was measured in UTT residual-limbs from the most medial aspect of the medial tibial condyle to the most distal point of the tibia. Subject measurements are shown in [Table 1](#).

2.3. Data analysis

Statistical analysis was conducted using Matlab (version 2016b, Mathworks Inc, Natick, MA, USA). Comparisons were made between both limbs of CS and both limbs of PWLL. The Shapiro-Wilks test was used to assess for normality at a significance of $p = 0.05$. Independent samples t -test was used to assess difference between CS, UTT intact, UTT residual, and BTF groups. A paired-samples t -test was used to assess difference between the UTT intact- and residual-limbs, and both limbs of CS ($\alpha = 0.05$). Muscle volume results were presented as percentages compared to CS ([Table 2](#), [Figs. 2](#) and [3](#)), and as a percentage of total muscle volume (TMV; [Table 3](#)). Vastii muscles were not included for BTF TMV. Multiple linear regression analysis was used to analyse the relationships between height, mass, femur-length, tibia-length, and pelvic-width with measured limb TMV. A model for predicting TMV (pTMV) using anatomical measurements was determined and compared against singular predictors for predicting V_m and TMV. The appropriateness of each regression model was checked by inspecting the normal probability plot of the regression residual and the scatterplot of the residual.

3. Results

3.1. Control subjects Inter-Limb difference

No data was held regarding CS dominant limbs. Therefore, every combination of dominant limb was determined and assessed for significant difference between each muscle. No significant differences were found in any combination. [Supplementary Data \(SD\) Figure S1](#) shows the inter-limb differences when comparing left-leg to right leg, whilst the p -values for the dominant limb combinations can be found in SD [Table S9](#).

Table 2
Muscle Volumes as a Percentage of CS].

Muscle	UTT Intact	SD	UTT Residual	SD	BTF	SD
Adductors	96.2^{*3}	15.9	89.4^{*2}	12.1	84.8^{*1}	12.6
Adductor Brevis	92.3 ^{*4}	16.1	87.0 ^{*4}	20.8	122.1 ^{*1,2,3}	27.9
Adductor Longus	82.0	18.1	74.0 ^{*1}	23.0	84.2 ^{*1}	9.8
Adductor Magnus	97.2 ^{*4}	17.0	91.1 ^{*4}	11.9	78.0 ^{*2,3,**1}	11.9
Gracilis	90.0 ^{*4}	32.2	83.3	30.7	58.3 ^{*2,3,**1}	18.2
Pectineus	102.5	15.7	97.3	12.4	116.7	27.8
Sartorius	107.5 ^{*+4}	17.5	98.7 ^{*+4}	17.9	76.9 ^{*3,**1,2}	15.0
Abductors	99.5^{*3}	14.4	88.8^{*4}	11.1	106.3^{*3}	15.0
Gluteus Medius	101.1 ^{*3}	19.1	86.1 ^{*1,2,**4}	10.1	110.4 ^{*1,**3}	12.7
Gluteus Minimus	107.0	14.9	101.0	17.3	103.0	24.6
Tensor Fasciae Latae	85.0	20.5	84.9	29.3	94.6	18.7
Gluteus Maximus	94.7	19.3	84.4	15.0	100.4	18.8
Iliopsoas	93.6^{*4}	11.3	94.5^{*4}	11.6	109.9^{*1,2,3}	12.6
Medial Hamstrings	83.6^{*1,**4}	18.6	73.2^{**1,4}	13.5	49.2^{**1,2,3}	13.6
Lateral Hamstrings	85.7^{*4}	11.9	84.7	15.5	61.5^{*2,**1}	24.8
Rectus Femoris	70.7 ^{**1,*3}	14.9	54.0 ^{*2,**1}	6.5	55.8 ^{*2,**1}	12.7
Vastii	96.7^{**3,4}	15.2	60.8^{**1,2,4}	8.1	39.4^{**1,2,3}	8.5
Vastus Lateralis	102.8 ^{**3}	5.6	67.7 ^{**1,2}	7.4	—	—
Vastus Intermedius	84.6 ^{*3}	24.9	49.6 ^{*2,**1}	13.7	—	—
Vastus Medialis	101.5 ^{**3}	21.7	63.2 ^{**1,2}	4.9	—	—
Gastrocnemius	90.4 ^{**3}	19.6	31.7 ^{**1,2}	11.8	—	—
Soleus	92.1	17.4	—	—	—	—
Total Muscle Volume	92.8 ^{**3,4}	14.8	76.9 ^{**1,2}	9.3	65.2 ^{**1,2}	12.5

Muscle volumes of UTT intact limb, UTT residual limb, BTT and BTF, expressed as a percentage of CS muscle volume. Statistical differences are shown with superscripts 1 (different from CS), 2 (different from UTT intact), 3 (different from UTT residual), 4 (different from BTF), with significance at the $p < 0.05$ and $p < 0.01$ levels denoted by * and **, respectively. **Bold** text shows results for muscle groups

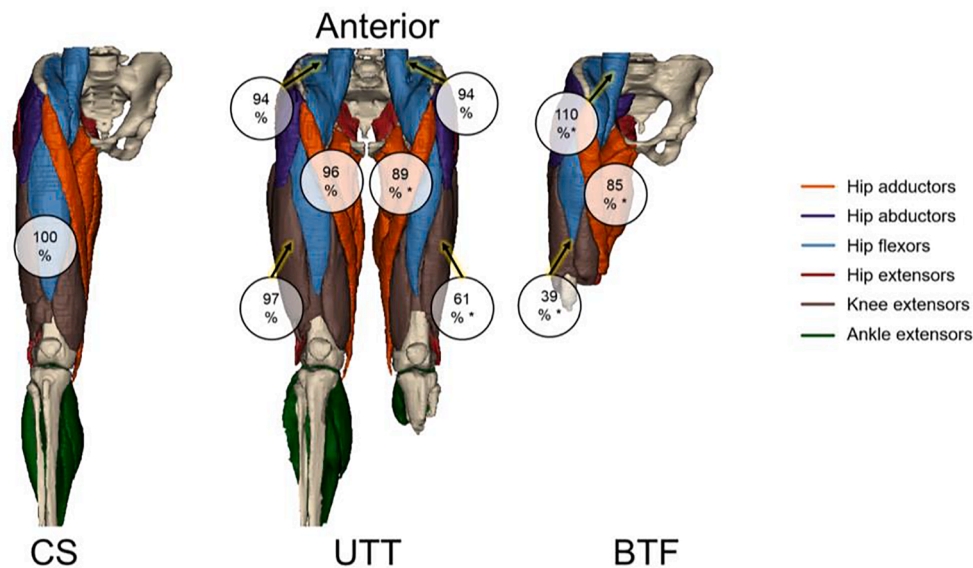


Fig. 2. Anterior muscle group comparisons of control subject and amputee subject groups. * denotes statistical difference to able-bodied subject. CS – control subjects, UTT – unilateral transtibial, BTF – bilateral transfemoral.].

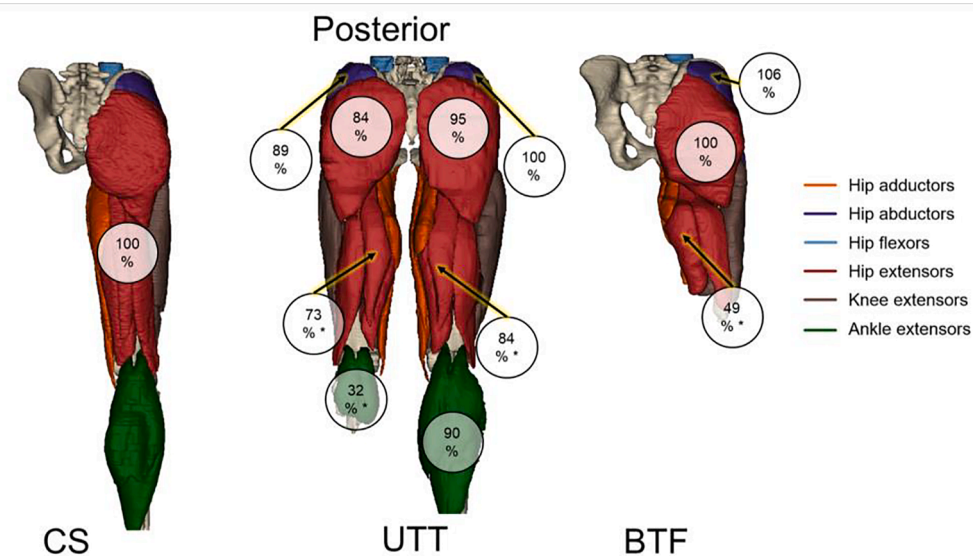


Fig. 3. Posterior muscle group comparisons of CS and PWLL subject groups. * denotes statistical difference to able-bodied subject. CS – control subjects, UTT – unilateral transtibial, BTF – bilateral transfemoral.

3.2. Unilateral-Transtibial amputations

In the UTT residual-limb, the hamstrings ($p = 0.001$, 27% and 15% smaller than CS for medial and lateral hamstrings, respectively), vastii ($p < 0.001$, 39% smaller than CS), rectus femoris ($p < 0.001$, 46% smaller than CS), gluteus medius ($p = 0.028$, 14% smaller than CS), and gastrocnemius ($p < 0.001$, 68% smaller than CS) muscles were all significantly smaller than the CS group, and, except for the hamstrings, were all significantly smaller than the UTT intact-limb. In the UTT intact-limb, the rectus femoris ($p = 0.004$, 29% smaller than CS) and the medial hamstrings ($p = 0.037$, 16% smaller than CS) were the only muscles significantly smaller than CS. In the UTT residual-limb, abductors, gluteus maximus, and rectus femoris were the smallest of all the subject groups (11%, 15%, 46% smaller than CS volume, respectively). No UTT residual- or intact-limb muscles were significantly larger than CS.

3.3. Bilateral-Transfemoral amputations

In BTF, all muscles with a pre-amputation insertion into the distal femur or below were significantly smaller than CS (adductor magnus [$p = 0.005$, 22% smaller than CS volume], rectus femoris [$p < 0.001$, 44% smaller than CS], sartorius [$p = 0.006$, 23% smaller than CS], gracilis [$p < 0.001$, 41% smaller than CS], vastii [$p < 0.001$, 60% smaller than CS], hamstrings [$p < 0.001$, 51% and 38% smaller than CS, medial and lateral hamstrings, respectively]). Adductor brevis [$p = 0.016$, 22% larger than CS], gluteus medius [$p = 0.040$, 10% larger than CS], and iliopsoas [$p = 0.020$, 10% larger than CS] were significantly larger than CS.

3.4. Regression models

Multiple linear regression models (Table 4) were used to explore relationships between individual muscles and TMV. For all subject groups, the best predictor for V_m was the multiple linear regression

Table 3

Muscle Volumes as a Percentage of Limb Total Muscle Volume.

Muscle % (SD)	Lit.	CS		UTT Intact		UTT Residual		BTF	
		%	SD	%	SD	%	SD	%	SD
Adductors	15.71	16.97	0.99	16.21	0.82	20.17	1.08	25.37	1.40
Adductor Brevis	1.64	1.48	0.32	1.51	0.09	1.89	0.31	3.48	0.47
Adductor Longus	2.56	2.84	0.32	2.53	0.21	3.07	0.83	4.63	0.39
Adductor Magnus	8.83	8.93	0.95	9.38	0.43	11.75	0.65	13.29	1.44
Gracilis	1.64	1.87	0.27	1.82	0.55	2.23	0.57	2.05	0.42
Pectineus	1.05	0.89	0.16	0.98	0.16	1.23	0.12	1.92	0.30
Sartorius	2.58	2.82	0.48	3.29	0.33	4.02	0.50	4.11	0.39
Abductors	7.77	7.59	0.37	8.13	0.81	9.67	1.03	15.24	1.57
Gluteus Medius	5.10	4.83	0.29	5.23	0.60	5.95	0.34	10.09	0.98
Gluteus Minimus	1.65	1.50	0.34	1.72	0.32	2.16	0.48	2.86	0.59
Tensor Fasciae Latae	1.02	1.27	0.17	1.19	0.32	1.56	0.52	2.29	0.28
Gluteus Maximus	13.39	14.18	1.46	14.44	1.17	17.17	1.48	26.84	1.48
Medial Hamstrings	6.80	7.11	0.56	6.30	0.74	7.38	0.58	6.56	1.48
Semitendinosus	2.93	3.19	0.42	2.88	0.56	3.65	0.55	–	–
Semimembranosus	3.87	3.92	0.50	3.42	0.49	3.73	0.79	–	–
Lateral Hamstrings	4.84	5.14	0.38	4.80	0.45	6.28	0.62	5.90	1.76
Iliopsoas	7.12	5.23	0.42	5.27	0.35	7.07	0.40	10.91	1.14
Rectus Femoris	4.24	4.84	0.39	3.72	0.60	3.78	0.36	5.07	0.55
Vastii	24.20	24.43	2.17	25.52	0.96	21.52	2.52	–	–
Vastus Lateralis	13.11	10.23	1.32	11.45	1.32	9.98	1.09	–	–
Vastus Intermedius	4.27	7.62	1.28	6.87	1.20	5.45	1.31	–	–
Vastus Medialis	6.82	6.58	0.35	7.20	0.49	6.08	0.62	–	–
Gastrocnemius	6.43	6.57	1.26	6.32	0.49	2.94	0.95	–	–
Soleus	6.91	6.04	0.80	5.98	0.44	–	–	–	–

Muscle volume fractions given as a percentage of the total leg muscle volume, comprising of the muscles listed here. Lit. - Literature values for total muscle volume have been adjusted to match the muscles in this study in order to enable comparison. Muscles that no longer span a joint and are not contributing to movement were not included in the volume fraction calculations (soleus in transtibial, vastii in transfemoral). **Bold** text shows results for muscle groups

Table 4

Multiple Regression Models for Determining pTMV for all Subject Classifications.

Control Subjects			Adjusted R ²	p Value
Regression Model:	Intercept + H.x1		0.752	0.00016
	B	SE	T-Stat	p Value
Intercept	–14408.45	3963.97	–3.63	0.00458
x1	128.67	21.96	5.86	0.000160
UTT Intact Limb			Adjusted R²	p Value
Regression Model:	Intercept + H.x1 + M.x2		0.802	0.0409
	B	SE	T-Stat	p Value
Intercept	11751.24	17119.90	0.67	0.542
x1	–83.79	104.68	–0.80	0.482
x2	130.91	32.42	4.038	0.0273
UTT Residual Limb			Adjusted R²	p Value
Regression Model:	Intercept + M.x1 + FL.x2		0.81	0.0386
	B	SE	T-Stat	p Value
Intercept	17501.85	5518.04	3.17	0.0504
x1	54.56	14.24	3.83	0.0313
x2	–405.37	135.26	–2.99	0.0578
BTF			Adjusted R²	p Value
Regression Model:	Intercept + H.x1 + M.x2 + FL.x3		0.865	0.00022
	B	SE	T-Stat	p Value
Intercept	–33338.49	5474.11	–6.09	0.00029
x1	245.17	40.12	6.11	0.00029
x2	–94.56	26.15	–3.62	0.0068
x3	41.72	22.54	1.85	0.101

Multiple regression models for predicting total muscle volume. H (cm) – height, M (kg) – mass, FL (cm) – femur length, PW (cm) – pelvic width, TL (cm) – tibia length

predictor model, pTMV. The best determinants of pTMV varied between subject groups, and its ability to explain measured TMV variation ranged from 75.2% to 86.5% for the small sample sizes here. In CS, height as a single predictor provided the model with the best fit, whilst height and mass, and height and femur length in the UTT intact-limb and residual-limb, respectively, provided the best fit for these groups. In the BTF group, height, mass, and femur length provided the model for the best fit. Single parameter linear regression models for each subject group are

presented in SD Tables S5–S9, as some single predictors were better able to estimate V_m than pTMV.

3.5. Supplementary data

Detailed muscle data for each group can be found in SD Tables S1–S4. Values for r^2 and the coefficients of best fit for height, mass, femur-length and pelvic-width can be found in SD Tables S5–S8. P-Values for CS dominant limb difference can be found in SD Table S9.

4. Discussion

The accurate determination of volume and physiological atrophic or hypertrophic state in muscles is essential for estimating F_{MAX} . In this study, high-resolution MRI was used to quantify lower-limb volume change patterns in PWLL, and for the identification of relationships between different anthropometric parameters for muscle model development.

4.1. Unilateral-Transtibial amputations

The whole-limb TMV loss in the UTT residual-limb and the minor volume changes in the intact-limb provide anatomical evidence for a compensation strategy in this population that is dominated by the intact-limb, as previously evidenced biomechanically in other studies (Winter and Sienko 1988, Norvell et al. 2005, Ding et al. 2020). The UTT intact-limb rectus femoris and lateral hamstrings were significantly smaller than CS. A key period of rectus femoris activity is the loading response phase (0–15% gait cycle; Annaswamy et al. 1999) where an eccentric contraction with the vastii muscles counteracts excessive knee-flexion. In both UTT limbs there is an increase in hip-flexion during this phase that continues to 50% of the gait cycle (Bateni and Olney 2002). This increase in hip-flexion, and corresponding increase in hip-flexor length at terminal stance, reduces the effective force production of the hip flexors, which provides a biomechanical explanation of the reduction in V_m compared to CS of these muscles, demonstrated externally by a decrease in hip power in both limbs during the loading response phase

(Bateni and Olney 2002).

The UTT residual-limb gluteus medius was shown to be smaller than the intact-limb (14% smaller than CS compared to 1% larger than CS for intact-limb). In previous studies, UTT subjects exhibited a decrease in hip power production and a lower maximum hip-extension prior to toe-off (Winter and Sienko 1988, Bateni and Olney 2002). This is likely to result from compensation strategies selected to reduce external moments around the residuum-socket interface at the knee for avoidance of pain (Lloyd et al. 2010, Jarvis et al. 2021) and provide explanations for decreased gluteus medius volume. These compensation strategies lead to the near-absence of the residual-limb knee power generation phase at mid-stance, and decreased knee power absorption phases at weight-acceptance, push-off, and during swing (Winter and Sienko 1988, Bateni and Olney 2002) and provide an explanation for the atrophy of the knee extensors in this limb seen in this study (residual-limb vastii 39% smaller than CS volume, $p < 0.001$).

The increased reliance on the intact-limb for power production shown previously (Winter and Sienko 1988, Norvell et al. 2005, Ding et al. 2020) would suggest an expected increase in UTT intact-limb ankle plantar flexor V_m , but this was not found. In our data, the compensatory demands placed on the powerful muscles of the ankle complex were not sufficient to induce hypertrophy in our participants.

4.2. Bilateral-Transfemoral amputations

The BTF results clearly support a compensation strategy dominated by the short adductor muscles (adductor brevis and pectineus), the hip flexors, and the gluteus medius. In BTF the vastii muscles are rendered functionally redundant and it is to be expected that these muscles show significant volume reduction. Other distally inserting muscles of the thigh (adductor magnus, gracilis, hamstrings, rectus femoris, sartorius) show less V_m loss than seen in the vastii, demonstrating despite muscle cleaving, some muscle recruitment is achieved. However, the significant reduction of biarticular hamstrings, rectus femoris, and gracilis V_m show that they are not being recruited to the same levels that they were prior to amputation. Biarticular muscles are essential for maintaining system postural stability in persons without amputation through control and co-ordination of the hip and knee joint in response to changes in upper body angular momentum (Schumacher et al. 2019). Amputation changes the function of these muscles from biarticular to monoarticular, and often results in muscles that are insufficiently tensioned and, subsequently, poorly recruited (Gottschalk 1999, Ranz et al. 2017). Methods to determine the role of these muscles in PWLL ambulation, and the effect of increased recruitment of these muscles on function and movement efficiency, should be investigated.

The smaller adductor magnus and sartorius V_m reduction (to 78% and 77% of CS, respectively) indicates these muscles remain contributory, even if a distal portion has been cleaved. Interestingly, in subjects with a complete femur and intact distal adductor magnus fixation, V_m loss of 10–15% compared to CS was observed. The ischio-condylar portion of the adductor magnus is also called the ‘hamstrings portion’ due to its shared tibial nerve innervation and function with the hamstrings muscles (Jeno and Schindler 2018). The atrophy seen in adductor magnus is in accordance with the reduced functional recruitment of the hamstrings in BTF, as opposed to the functional recruitment of the adductors. This degeneration of the hamstrings portion rather than the adductor portion is supported by the evidence of Putz et al., (2017) whereby “nearly no fatty degeneration” of the adductor muscles were found in the middle of the residuum, where the muscles are innervated by the obturator nerve. The adductor brevis and the pectineus both exhibit volume increases compared to CS ($p = 0.016$, 22% and $p = 0.131$, 17% larger than CS, respectively) demonstrating the vital role of these muscles to the BTF compensation strategy. The loss of the distal insertion of the adductor magnus in many transfemoral amputations causes an overall reduction in effective moment arm of the adductor group (Gottschalk 1999), and the remaining adductor muscles must

compensate to maintain postural stability, providing a mechanical explanation for the increase in specific V_m .

BTF gluteus medius was the largest of all the subject groups ($p = 0.023$, 10% larger than CS). BTF have been shown to adopt a larger stride width than persons without amputation (Chang et al. 2011, Whittle 2014, Jarvis et al. 2017). Walking with wider steps is known to increase gluteus medius activity during stance (Kubinski et al., 2015) for stability and power production. The increases in stride-width shown in BTF in the literature provides a mechanical explanation for the increases shown in this study. The BTF iliopsoas complex is also the largest of all groups ($p = 0.020$, 10% larger than CS) due to hip-flexor compensation for the absent ankle plantar flexors for the generation of swing-through at push off.

Multiple linear regression models were presented to estimate muscle volumes using readily measurable anthropometric parameters. Whilst the accuracy of the models was good within the subject anthropometry ranges in this study, and comparable to reported values in a similar study (Handsfield et al. 2014), the relationships between height, mass, and TMV in the CS group were less robust than were found by Handsfield. This may result from the small sample size in this study, and because this study presents both limbs of persons without amputation, and the minor inter-limb differences create larger variability to be accounted for using the same metrics, as a subject’s height and mass are constants regardless of which limb was being considered. The impact of minor length differences in femur-length did not account for these inter-limb muscle variations, and may result from subtle inter-limb muscle recruitment differences that occur in every person during movement or recreation. There is a strong relationship between maximum femur-length and height (Hauser et al. 2005) in a normal population, and this relationship, combined with the use of a femur-length determined from anatomical landmarks rather than maximum length, meant that the inclusion of femur-length in the CS regression model weakened the model. The models presented for PWLL in this study were more robust than CS due to the more explicit inter-limb differences that can be accounted for using height and mass variables, particularly when combined with femur-length in the BTF subject group. This allowed the model to account for 85% of differences in TMV in BTF. The inclusion of tibia-length in the UTT residual limb model reduced the effectiveness of the predictor model. All UTT subjects presented with very similar, non-normally distributed tibia lengths, likely because of surgical guidelines for ideal tibia length (Lam et al., 2016) and this lack of variation prevents its utility as a predictor in this subject cohort.

There were limitations to this study. Primarily, the small group sizes limit the wider data applicability, as the variations seen in this study do not account for extreme heights and body masses, and do not consider the effect of gender on V_m . Additionally, the similarity in time-since-amputation in PWLL subject groups meant that this could not be analysed for effect on muscle volume. A larger, more diverse sample may see a relationship between time since amputation and muscle volume and should be considered in future research. Muscle volume changes can occur through chronic over-or under-use; a study on a group of PWLL (Stepien et al. 2007) of mean age of 65 years had an average daily step count of 3063, whilst a study on persons without amputation showed the average adult daily step count to be ≈ 5100 steps-per-day (Basset Jr. et al. 2010). However, the 65 year old age group of this second study had a step count closer to PWLLs (≈ 4000). Without in-depth knowledge of the individual’s activity levels, it is impossible to separate the effect of under-activity and compensation strategy. However, the maintenance of muscle volumes in the intact limb of the UTT group to CS suggests similar levels of activity and, hence, that the anatomical changes were a result of compensatory movement patterns employed to walk with a prosthesis. Muscle composition, such as the proportion of fatty content, also affects how a muscle produces force. This was not examined in this study and therefore limits the wider utility of the results as muscle quality could not be established. Multiple hypothesis tests were conducted on the data obtained for this study, creating a risk that some of

the statistically significant results were false positives (Type I error). However, the impact of a false positive was considered to be much lower than the impact of a false negative (Type II error), which could lead to a missed opportunity for productive intervention (Armstrong 2014). Hence, corrective measures such as the Bonferroni correction, were not applied to reduce occurrences of Type II statistical error.

5. Conclusion

Amputation and the subsequent return to movement requires the development of compensation strategies, and these strategies, over time and assuming a maintained level of activity, lead to localised occurrences of muscle atrophy and hypertrophy dependent upon muscle recruitment within the new body schema, despite these muscles remaining fully innervated and offering force producing potential within a limited system. This study provides a benchmark measure of muscle volume discrepancies for individuals with and without limb-loss. Understanding the compensation strategy and its impact on muscle volume as presented here can be used to gain insight of the compensation strategy of persons with limb loss and its impact on muscle volume, thus enabling targeted and informed rehabilitation interventions, surgical techniques, and prosthetic devices that promote and enhance functional capability within the population of persons with limb loss.

Declaration of Competing Interest

The authors wish to report no known conflicts of interest or competing relationships that could have influenced the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2021.110599>.

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