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Functional quadriceps reconstruction: 3D gait analysis, EMG and environmental simulator outcomes

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KEYWORDS

Sarcoma;
Functional quadriceps;
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Abstract *Object:* Limited objective evidence exists on the benefits of functional muscle transfers following quadriceps resection in sarcoma. In particular, no studies have compared patients with functional transfers to those without. In this study, objective and subjective assessments were performed with 3D Gait Analysis, Environmental Simulator, Electromyography (EMG) and Patient-Reported Outcomes.

Methods: Thirty-four patients at the Scottish Sarcoma Network Glasgow Centre/ Canniesburn Plastic Surgery Unit underwent quadriceps resection for sarcoma between 2009 - 2019, including 24 patients with functional reconstruction and 10 without. Both groups were equivalent for the extent of quadriceps resection (2.58 versus 2.85 components, $p=0.47$). Primary outcome measure was 3D Gait Analysis and Gait Profile Score (GPS), and secondary outcome was the Toronto Extremity Salvage Score (TESS) score. Ancillary analyses included environmental simulation with the Motek CAREN system and EMG of transferred muscles.

Results: Outcomes measures were better in functional reconstruction patients when compared to those without - the GPS score was 8.04 versus 10.2 ($p=0.0019$), and the TESS score was 81.85 versus 71.17 ($p=0.028$). Environmental simulator tasks found that functional reconstruction patients could complete activities of daily living including shopping and collision avoidance tasks,

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without significantly slowing their walking speed. Patients without a functional reconstruction could not complete weighted shopping tasks. EMG showed that transferred hamstrings co-activated with the ipsilateral rectus femoris during the gait cycle.

Conclusions: These are the first objective data demonstrating the superiority of muscle transfers for functional restoration in quadriceps resection versus patients without functional transfers. Critically, these also provide answers to patient-oriented questions relating to the recovery of function and activities of daily living.

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Introduction

A need for functionally relevant outcome measures in quadriceps reconstruction

Functional muscle transfers for quadriceps reconstruction, such as hamstring or sartorius transfers, have historically been described in the management of poliomyelitis for over a century.^{1,2} Recently, these have been repurposed in the management of sarcoma resection of the quadriceps and have been augmented with the use of Free Functional Muscle transfers.^{3,4}

These have been described in relatively small cases series, with the interpretation of previous study outcomes commonly affected by two key methodological flaws. Firstly, outcome measures have been limited to subjective measurements prone to investigator bias such as physical measurements, or having limited real world applicability to patients, including the Musculoskeletal Tumour Society score (MSTS) or dynamometry. For example, it is meaningless to patients to tell them that they will have an MSTS score of 20 post-surgery, or that their quadriceps strength will be MRC grade 4, or that their isometric strength will be 30% reduced. Even clinicians cannot contextualise these scores for their patients. Other studies have used invalidated and intangible outcome measures such as “good” or “excellent”. None of these measures are of functional relevance and cannot be used to inform a patient whether they will be able to walk normally again after surgery.^{3,5-7}

Secondly, no previous study has compared functional transfers for quadriceps reconstruction with a control group. This makes the interpretation of the benefits of the muscle transfer meaningless, as outcome measures will be confounded by residual quadriceps components that are left in-situ post-resection.

Residual quadriceps function confounds outcome measurements after muscle transfer

In all previous studies, the interpretation of the true contribution of muscle transfers is confounded by heterogeneity in the amount of quadriceps resection, variations in the type of functional reconstruction and a lack of control groups. BG University Hospital Bergmannsheil, Germany, analysed 17 patients with physical measurements, dynamometry and patient-reported outcomes.⁵ This provided data on ham-

string and gracilis transfers, including estimates of knee extension strength at 44% in comparison to the contralateral leg. However, this study had no comparison group, did not employ validated sarcoma outcome instruments such as TESS, and the results are difficult to contextualize for patients. The Washington Cancer Institute, USA, evaluated 15 patients with pedicled muscle transfers using MSTS and physical examination.³ In this series, sartorius or biceps femoris transfers had extensor lag 4-6°, power was 4.2-4.75, and MSTS score was ‘good’ or ‘excellent’ in 100%. Given that these were performed in patients with 2 or 3 residual quadriceps, the excellent outcomes in these pedicled transfers may reflect residual quadriceps function rather than the muscle transfers per se. Innocenti et al. reported 11 cases of free functioning latissimus dorsi,⁶ with MSTS ratings ranging from ‘good’ to ‘excellent’ in 73% of the cases. However, these results were confounded by additional pedicled muscle transfers in 36%, there were a lack of objective outcome measures, and there was no control group. Muramatsu et al. reviewed 14 free functional latissimus dorsi transfers without additional pedicled muscle transfers and noted that functional outcomes correlated strongly with the degree of quadriceps resection,⁸ with total quadriceps resection resulting in very poor functional results. Valid interpretation of the contribution of muscle transfers in all of these studies is not possible due to confounding by residual quadriceps function, emphasizing the critical need for a comparator group of quadriceps resections that have not undergone muscle transfer.

3D Gait Analysis, Environmental Simulator and Electromyography

In addition to addressing methodological flaws relating to invalidated outcome measures and a lack of control groups, there are also a number of key patient questions that are of functional relevance. This study aims to answer these questions by using validated outcomes compared to a control population, which includes:

“Can I walk again after this operation?”

“Can I go shopping again?”

“Can I go out on the street and be able to avoid bumping into people?”

“Will I need to use crutches or a knee brace?”

This study investigated patients with objective testing using standardised 3D gait analysis, which leverages 3D camera technology and floor pressure sensors to provide a far greater degree of sensitivity and objectivity than other measures such as visual gait analysis, isometric strength and patient-reported outcomes. It also provides a key outcome measure, the Gait Profile Score (GPS), which quantifies the deviation between pathological and healthy unimpaired populations⁹ and has been used to assess the impact of surgical interventions in cerebral palsy⁹ and lower-limb amputations.^{10,11}

To investigate the return of activities of daily living, an environmental simulator (Motek CAREN system, Amsterdam, Netherlands) was used to recreate virtual shopping, weighted carrying and collision avoidance tasks. This was supported by the Toronto Extremity Salvage Score (TESS), a patient-reported outcome measure (PROM) widely used in sarcoma.¹² By using such an approach, it is hoped that specific questions about the recovery of function and activities of daily living can be answered for patients, and that objective data can be provided to inform and inspire future research.

Methods

The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines for cohort trials were followed for this study. Regional Ethics Committee (18/NW/0165) and site specific management approvals from Strathclyde University and WestMARC Centre were obtained in line with Greater Glasgow and Clyde R and D board requirements. NCT04911972 is the ClinicalTrials.gov identifier. Patients consented in writing to participate.

Participants and Setting

Thirty-four patients in the Scottish Sarcoma Network Glasgow Centre / Canniesburn Plastic Surgery unit underwent quadriceps resection between 2009 and 2019, of whom 24 underwent quadriceps functional reconstruction and 10 without. Quadriceps resection was defined as cross-sectional resection of muscle, classified as total or partial per muscle component. Inclusion criteria - age 18-95 years; at least 1 quadriceps component resection; > 3 months post-surgery. Exclusions include: active treatment of complications or metastases; < 3 months post-surgery; actively undergoing radiotherapy; and motion sickness (environmental simulator).

Data were collected prospectively, PROMs were collected between 2009 and 2020 (n=27, 100% eligible participants), and 3D gait analysis was collected between 2016 and 2020 (n=17, 81% eligible participants). PROMs were collected as part of routine post-op care, and gait analysis forms part of the normal rehabilitation pathway in complex reconstructions since 2016. Ten patients were deceased at the start of the 3D gait analysis data collection period, and three patients passed away during the data collection period (Flowchart 1).

The 3D gait analysis was performed at the WestMARC centre, which is an internationally accredited lab (Clinical

Movement and Analysis Society, UK and Ireland) (Figure 1; Supplementary Video 1) - using a Vicon Giganet system with 10-bonita cameras (Vicon, Oxford, UK) and two AMTI BP400600 force platforms (Watertown, MA, USA). Data were collected with participants walking barefoot and using any walking aids they normally used, over ten gait cycles.¹¹ Environmental simulation was performed on the CAREN Motek system at Strathclyde University, Glasgow, using a large virtual screen, treadmill system and pressure sensors (Figure 2; Supplementary Video 2). Statistical analysis performed with SocSciStatistics, with a significance level of $p=0.05$.¹³

Outcomes

Primary outcome was GPS, and secondary outcome was TESS score. Ancillary analyses included Environmental Simulator and Electromyography (EMG). EMG was performed for the analysis of transferred muscle function and did not form a comparative outcome measure.

Missing Data

Seventeen of 21 (81%) eligible patients participated in 3D gait analysis, and 27 of 27 (100%) eligible patients for the TESS score. Missing data were treated as missing completely at random or missing at random.

Sample Size

Pilot trial data was used to calculate sample size based on GPS as primary outcome,¹⁴ giving 7 in intervention and 2 in control group for unequal group sizes (power 90%, significance 0.05, 2 sided). Using TESS data as a secondary outcome gave sample size of 19 intervention and 6 control group (Supplementary Table 1). Given the rarity of this surgery, pilot data was included as an internal pilot into the main trial.

Results

Sociodemographic Variables

Twenty-one patients underwent pedicled muscle transfers (Figures 3-6), and three had free functional muscle transfers (Figures 7-9). Five patients in the non-functional group had flaps for implant cover only. In these cases, the muscle was not attached to the patella as per functional transfers (Table 1). Walking aids were used by 29% in the functional group (3 crutches and 4 walking sticks) and 70% in the non-functional group (4 crutches, 4 knee braces, and 1 wheelchair) (Chi-square, $p=0.0275$). MRC power and range of motion were not used as outcome measures, due to low functional relevance and criticism of their use in lower limb studies,¹⁵ although are given where available (Supplementary Table 2).

Table 1 Sociodemographic and Clinical Variables

	Patient	Age (at the time of surgery)	Sex	Side	Tumour	Endo prosthesis	Resection	Femoral nerve intact	Functional Reconstruction	Radiotherapy	Walking Aids	Brace
Functional Reconstruction	1*	63	F	L	Chondrosarcoma	Yes	VM,VI,VL	Yes	LHBF, Sartorius, Gracilis	Adjuvant	No	No
	2*	45	F	L	Triton tumour/ Spindle cell	No -allograft	VM	Yes	LHBF, Sartorius	No	Walking Stick	No. Temporary knee brace for stress fracture.
	3*	72	F	L	Pleomorphic	No	VM,VI,VL,RF	No	LHBF, Sartorius	Adjuvant	No	No
	4	40	F	R	Osteosarcoma	No -allograft	VM,VI,VL,RF	Yes	Sartorius, Gracilis	No	No	No
	5*	43	M	L	Pleomorphic	No	VM,VI,VL,RF	Yes	LHBF, Sartorius	Adjuvant	Walking stick	No
	6	18	M	L	Osteosarcoma	Yes, complicated by fall	VM,VI,VL	Yes	LHBF, Sartorius	No	Crutches	No
	7	73	M	R	Leiomyosarcoma	No	VM,VI,VL	Yes	LHBF	Adjuvant	Occasional walking stick	No
	8	50	F	L	Chondroblastic osteosarcoma	Yes, mechanical failure req total fem EPR	VL,VI	Yes	LHBF, Sartorius	No	Crutches	No
	9	32	F	R	Pleomorphic	Yes	VM,VI,VL,RF	No	LHBF, Sartorius	Adjuvant	No	No
	10	64	M	R	Hybrid fibromyxoid/epithelioid fibrosarcoma	Yes	VL,VI	Yes	LHBF	No	No	No
	11	56	M	R	Myxoid Liposarcoma	No	VL,RF(50%), VI(50%)	No. Fem A +V graft	Rectus abdominis (functional - innervated) + FFMT (LD)	Neoadjuvant	No	No
	12*	57	M	L	Osteosarcoma	Yes	VL	Yes	LHBF, Sartorius	No	No	No
	13	53	M	L	Synovial	No	VM,VI,VL	Yes	LHBF, FFMT (RF)	Neoadjuvant	No	No
	14**	21	M	R	Osteosarcoma	Yes	VM(50%),VI,VL	Yes	LHBF, Sartorius	No	No	No
	15	17	M	L	Osteosarcoma	Yes	VM,VI,VL	Yes	LHBF, Sartorius	No	No	No
	16	36	F	L	Spindle Cell	No	VL,VI	Yes	LHBF	Adjuvant	No	No

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Table 1 (continued)

Patient	Age (at the time of surgery)	Sex	Side	Tumour	Endo prosthesis	Resection	Femoral nerve intact	Functional Reconstruction	Radiotherapy	Walking Aids	Brace	
17*	74	F	L	Spindle Cell	No	VM,VI,VL,RF (necrosis)	Yes	FFMT (ALT-Rectus Femoris) as salvage procedure	Adjuvant	No	No	
18	44	M	L	Liposarcoma	No	VL,RF	Yes	FFMT (ALT-Vastus lateralis)	Adjuvant	No	No	
19	38	M	L	Aggressive Aneurysmal Bone Cyst	Yes	VM,VI	Yes	LHBF, Sartorius	No	Occasional walking stick	No	
20	59	M	R	Rhabdomyosarcoma	No	VI,VL	Yes	LHBF	No	No	No	
21	43	M	R	Chondrosarcoma	Yes	VM	Yes	Sartorius	No	No	No	
22	17	F	L	Osteosarcoma	Yes	VM,VI,VL	Yes	LHBF, SHBF, Sartorius	No	Occasional walking stick	No	
23	20	F	R	Osteosarcoma	Yes	VI,VL	Yes	LHBF, Sartorius	No	No	No	
24*	23	M	R	Ewing's	Yes	VM,VI,VL(50%)	Yes	Sartorius	No	No	No	
Non-Functional Reconstruction	25*	83	M	R	Pleomorphic	No	VM,VI,VL,RF	Yes	No	Adjuvant	Wheelchair bound	Wheelchair bound
	26*	16	M	R	Osteosarcoma	Yes	VM,VI,VL	Yes	No. Sartorius for implant cover only	No	No	Knee brace
	27	17	M	R	Osteosarcoma	Yes	VM,VI,VL(50%)	Yes	No. Sartorius for implant cover only	No	No	No
	28*	62	M	R	Liposarcoma	Yes	None (Femoral Nerve resected)	No.	No	Adjuvant	Crutches	No

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Table 1 (continued)

Patient	Age (at the time of surgery)	Sex	Side	Tumour	Endo prosthesis	Resection	Femoral nerve intact	Functional Reconstruction	Radiotherapy	Walking Aids	Brace
29*	22	M	R	Osteosarcoma	Yes		Yes	No. Sartorius for implant cover only	No	No	No
30	18	M	L	Ewing's	Yes	VM,VI,VL(50%) VM,VI,VL	Yes	No	No	No	Knee brace (as knee gives out occasionally) Knee brace
31	52	M	R	Osteosarcoma	Yes		Yes	No	No	Crutches	Knee brace
32	82	M	L	Myxofibrosarcoma	No	VM,VI,VL,RF	Yes	No. Salvage wound breakdown with Rectus abdominis (non-functional - not innervated) + MSAP	Neoadjuvant	Crutches	Knee brace
33	19	M	L	Osteosarcoma	Yes	VM	Yes	No. Sartorius for implant cover only	No	No	No
34	52	F	L	Pleomorphic	No	VM,VI	Yes	No	Adjuvant	Crutches	No

* patient passed away prior or during data collection period

** lost to follow-up - did not attend follow-up clinicsLHBF - Long Head Biceps FemorisSHBF - Short Head Biceps FemorisFFMT - Free functioning muscle transfer

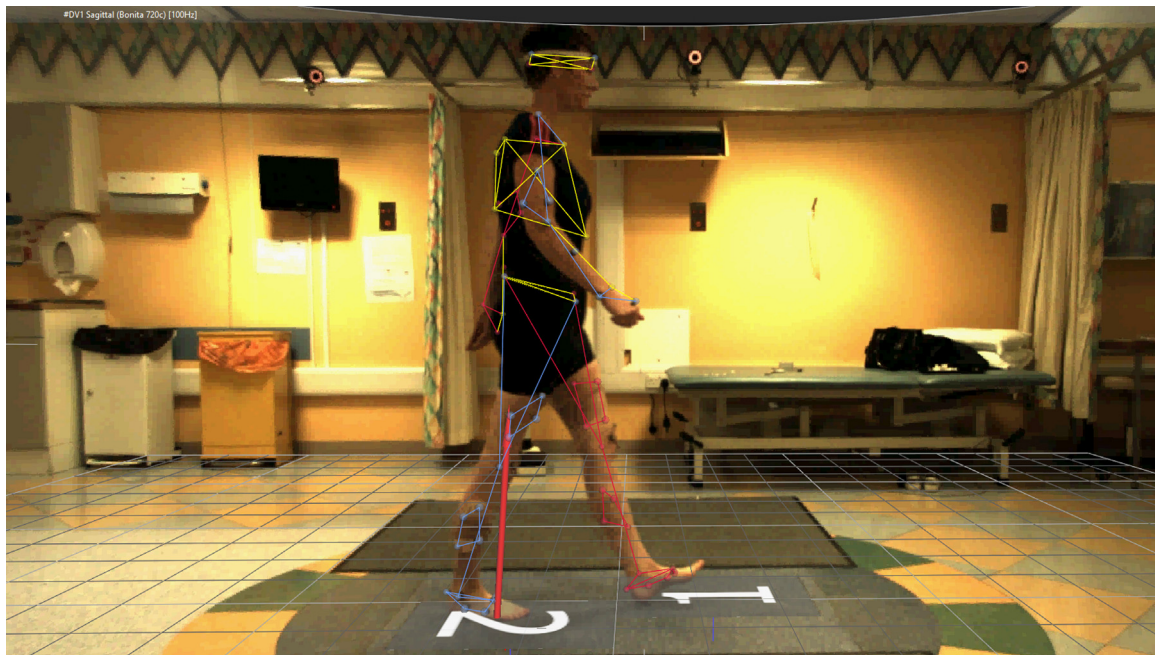


Figure 1 Patient with quadriceps reconstruction in the 3D Gait analysis laboratory with 3D model overlay.



Figure 2 The Motek CAREN system with a treadmill system, safety harness for patient and a large virtual reality screen. The system is equipped for 3D Gait analysis, whilst the patient navigates a virtual environment. This can test a patient's gait whilst they perform activities of daily living.

Equivalency of Functional and Non-functional Groups

A number of quadriceps resected were 2.58 in the functional group and 2.85 in the non-functional group ($p=0.47$). Other factors known to affect functional outcomes were compared between groups including age, sex, radiotherapy and endoprotheses, with no significant differences (Table 2).

Primary Outcome: 3D Gait Analysis

Functional reconstructions had significantly better GPS than in non-functional reconstructions (mean 8.04, 95% CI 7.49-8.49 versus 10.2, 95% CI 9.21-11.12) ($p=0.0019$, independent t-test, 2 tailed). Cohen's $d = 2.94$ indicating a 'huge' effect size. The only difference in subdomains between groups was step time symmetry (mean 0.91, 95% CI 0.88-

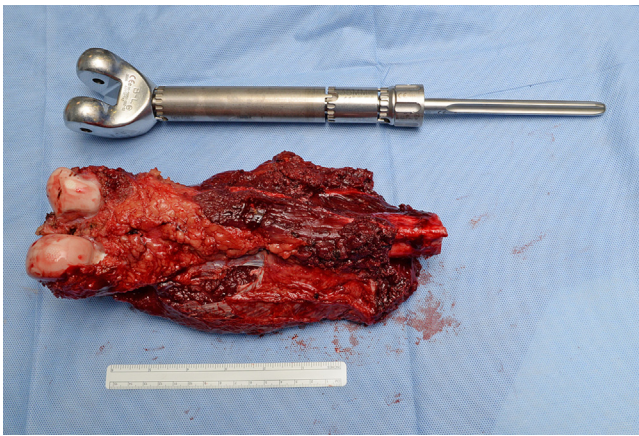


Figure 3 Distal femur sarcoma excision with 3 components resection adjacent to endoprosthesis.

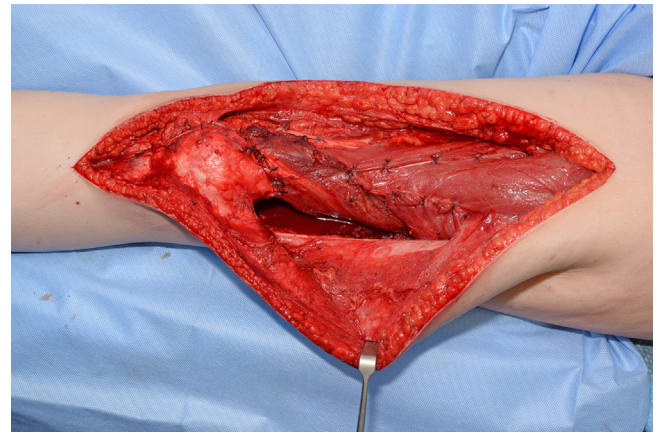


Figure 6 Neo-quadriceps created by sartorius centralisation with the long head biceps femoris sutured to the patella and side-to-side.

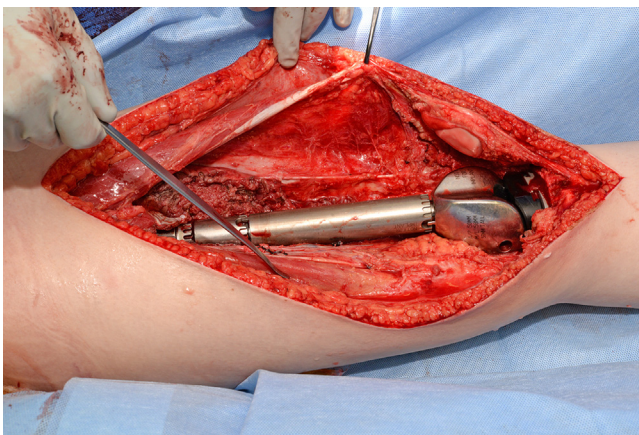


Figure 4 Residual defect with endoprosthesis in-situ. RF is only residual quadriceps component left. The instrument is pointing towards the long head of biceps femoris prior to raising.



Figure 7 Total quadriceps loss after resection, radiotherapy and secondary wound breakdown, with the exposure of bone and femoral artery.

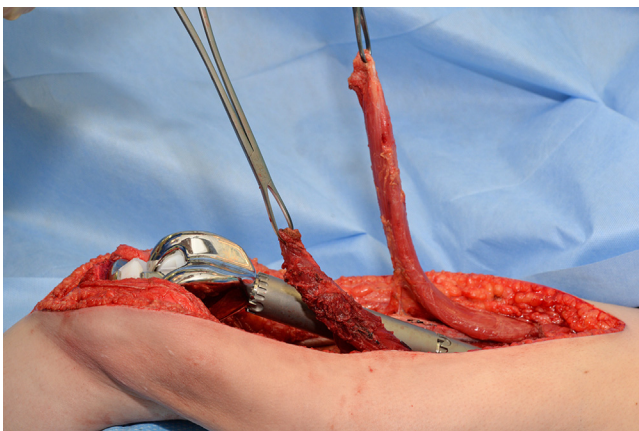


Figure 5 Sartorius (proximal) and long head biceps femoris (distal) as shown from the side.

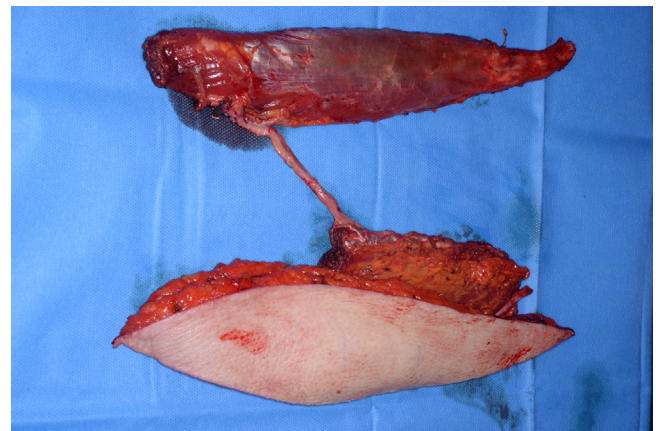


Figure 8 Anterolateral thigh (ALT) -RF free functional muscle flap. A small portion of the vastus lateralis has been raised to cover the exposed distal femur and prevent adherence of RF to the bone, and thereby facilitate glide.

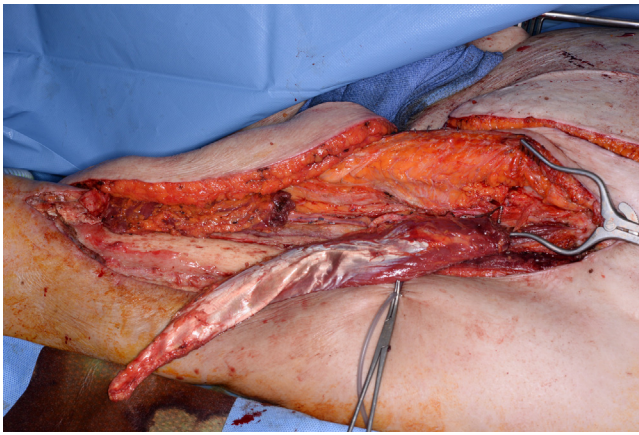


Figure 9 Combined flap in-situ but with RF not inset to patella. Exposed femur visible distally. A ORAM flap is present proximally to cover the proximal extent of the wound bed.

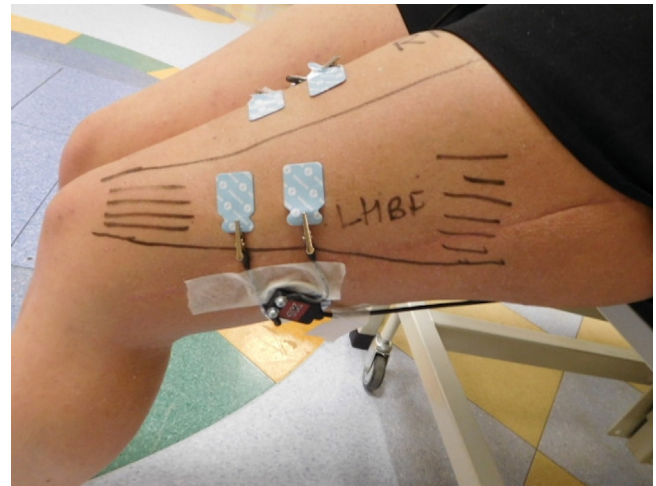


Figure 10 EMG sensors placed on the long head biceps femoris transfer and on the ipsilateral residual RF to assess for co-activation of transferred muscle with residual quadriceps. See Supplementary Digital Content 6 and 7 for corresponding intra-operative photographs.

Table 2 Comparison between Groups

	Functional reconstruction	No Functional Reconstruction	Significance
Age (years)	44.6	42.3	p=0.779**
Sex	10F: 14M	1F: 9M	p=0.07 ⁺
Number of quadriceps components*	2.58	2.85	p=0.47**
Endoprosthesis (EPR)	13 EPR: 11 none	7 EPR: 3 none	p=0.39 ⁺
Radiotherapy (DXT)	10 DXT: 14 none	4 DXT: 6 none	p=0.77 ⁺

* femoral nerve resection equivalent to 4 component resection

** Independent t test, 2 tailed

⁺ Chi-square test

0.94 versus 0.82, 95% CI 0.62-1.02 95%) (p=0.034, independent t-test, 2 tailed). Cohen's d = 1.31 ('very large' effect size) (Table 3).

Secondary Outcome: Patient-Reported Outcomes

TESS mean sum score was better in the functional reconstruction group at 81.85 (95% CI 77.12-86.58) versus in the non-functional group 71.17 (95% CI 64.43-77.91) (Independent t-test, 2 tailed, p=0.028). Cohen's d=1.07 indicates a 'large' effect size (Table 4).

Re-Analysis of Data with ≥ 2 component resections only

The primary and secondary outcomes were re-analysed with the inclusion of patients with a resection of ≥ 2 quadriceps components only. All outcomes remained significant (Supplementary Table 3).

Time to Testing intervals

No significant differences in time to testing were noted between groups for measurement of primary (3D Gait Analysis) or secondary outcomes (PROMs) (Tables 3 and 4).

Ancillary Analyses

Environmental Simulator

Nine patients underwent further optional participation in the CAREN Motek simulator. Patients underwent 3D gait analysis in real-time in the virtual reality simulated environment whilst performing a "shopping" task (pushing an imaginary shopping cart to pick up ingredients to make a pizza), a "collision avoidance" task (avoiding oncoming seagulls - requiring patients to make sudden side-step transitions), and walking with weighted bags task (1 kg per side). Functional reconstruction patients did not slow down significantly when carrying weighted bags (0.89 versus 1.0 m/s, p=0.64) nor with collision avoidance tasks (0.89 versus 0.92 m/s, p=0.88). This indicated that patients can go shopping and perform collision avoidance as normal, without having to stop, hesitate or slow down. Patients without functional reconstruction were unable to complete the weighted bags task (Functional reconstruction - successful task completion n=7, non-functional n=0, Fisher's exact test, p=0.028). (Supplementary Table 4)

Electromyography

Ancillary analysis of EMG synched with 3D gait analysis during walking (n=3) indicated that the transferred long head of the biceps femoris fires in phase with the ipsilateral rectus femoris during the gait cycle (Figures 10 and 11; Supplementary Figures 1 and 2; Supplementary Video 3). During

Table 3 3D Gait Analysis Data

Group	Patient	Follow-up Interval (months)	GPS (degrees)	Walking Velocity (m/s)	Step length (m)	Fz Symmetry	Step Length Symmetry	Step Time Symmetry	Knee Flex/ext (degrees)
Functional Reconstruction	4	40	6.8	1.3	0.68	3.7	0.96	0.91	6.3
	6	22	7.9	1	0.61	13.9	0.84	0.86	11.5
	7	16	8.4	0.62	0.47	1.54	0.921	0.957	21.8
	9	22	7.6	1.2	0.64	4.17	0.93	0.92	8.3
	10	5	7.3	1	0.57	7.53	0.9	0.95	13.8
	11	17	9.5	0.95	0.51	3.3	0.9	0.91	21.3
	13	8	8.4	0.89	0.54	4.9	0.89	0.85	13.5
	16	6	7.5	1.2	0.63	2.66	0.9	0.96	5.2
	18	8	6	1.7	0.88	7.6	0.99	0.98	8.1
	19	8	8.6	0.41	0.28	16.75	0.88	0.83	12
	20	105	8.3	1.3	0.66	13.2	0.91	0.88	17.6
	21	94	8.8	1.1	0.59	0.94	0.94	0.99	4.2
	22	11	9.4	0.87	0.6	15.1	0.89	0.82	8.8
23	12	8.1	1.25	0.66	3.4	0.87	0.89	13.5	
Non-functional Reconstruction	30	42	10.2	0.92	0.61	7.77	0.87	0.74	12.9
	31	59	9.8	0.7	0.46	8.6	0.93	0.9	12.6
	32	9	10.6	0.6	0.38	5.37	0.88	0.82	15.8
Mean of groups, significance		26.7 vs 36.7, p=0.63	8.04 vs 10.2, p=0.0019*	1.06 vs 0.74, p=0.119	0.59 vs 0.48, P=0.200	7.05 vs 7.25, p=0.952	0.91 vs 0.89, p=0.529	0.91 vs 0.82, p=0.034*	11.85 vs 13.77, p=0.571

* significant at p=0.05 level

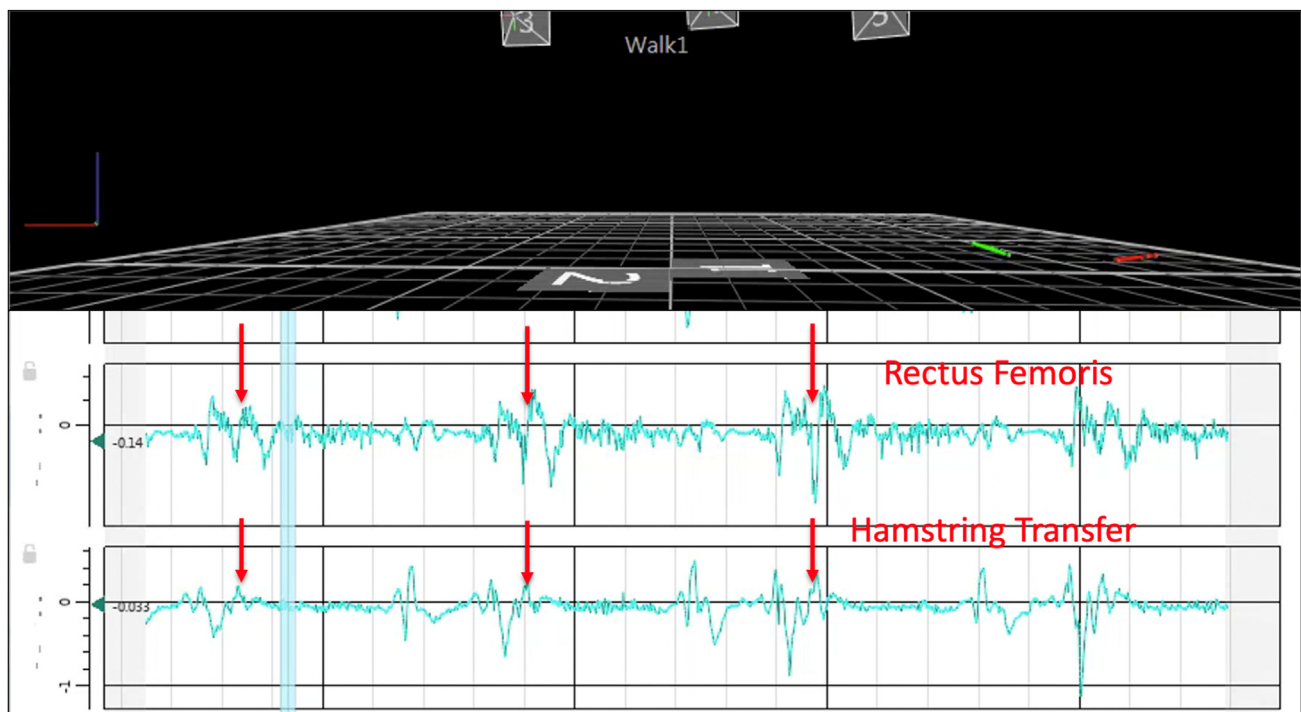
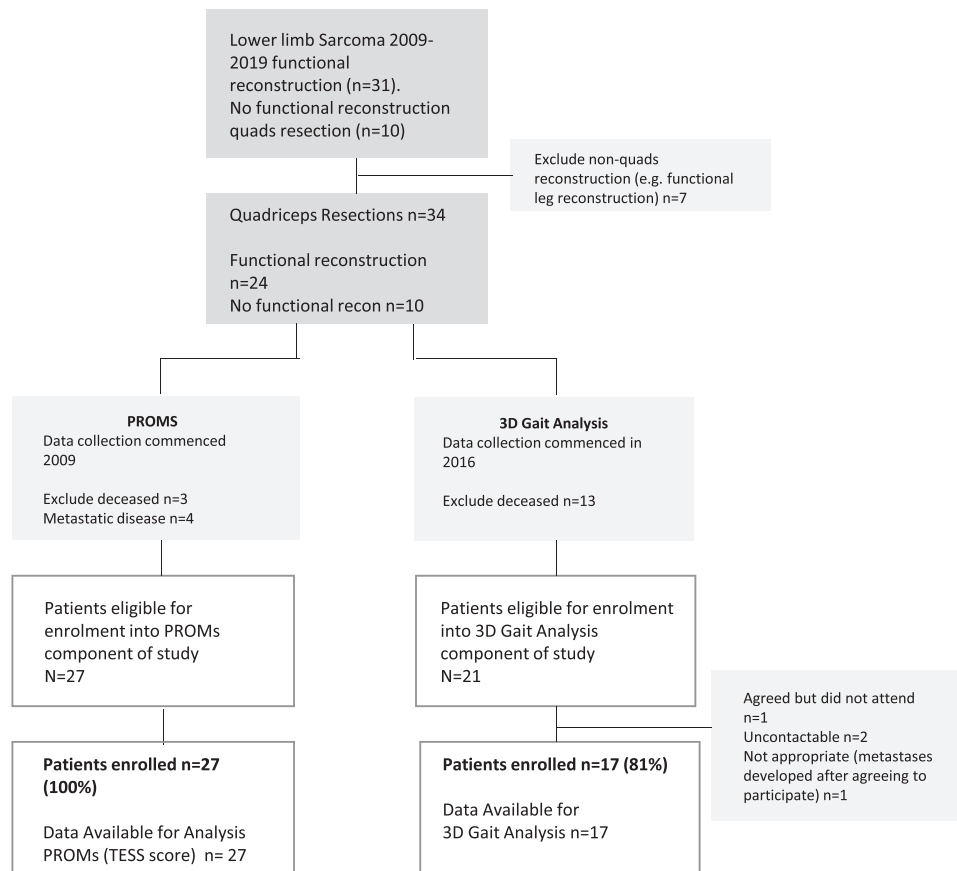


Figure 11 EMG synced with 3D gait analysis. The upper EMG trace is the ipsilateral RF and the lower trace is the hamstring transfer. The red arrows indicate the reconstructed leg in stance. The upper graphic shows the synced 3D gait analysis, with the green foot represents the normal side and the red foot represents the reconstructed side. See Supplementary Video 3 for more details.



Flowchart 1 Flowchart of participant recruitment for primary and secondary outcome measures.

seated leg extensions, EMG showed that transferred biceps femoris fires in phase with ipsilateral rectus femoris during extension and isometric contraction.

Harms

No harms were recorded in this study. No cases of disease recurrence occurred in the hamstring transfer donor site (posterior compartment thigh). No genu recurvatum or lateral dislocation of the patella were noted.

Discussion

The data presented here represent the largest comparative study worldwide on functional lower limb reconstruction after quadriceps resection, with data prospectively collected over a decade. This details describes the recovery of function after quadriceps reconstruction using a truly objective form of assessment in 3D Gait Analysis, and it, significantly, employs a control group without muscle transfers. Here, we demonstrate using 3D gait analysis, PROMs and environmental simulator tasks that functional muscle transfers result in a more normal gait than patients without a functional reconstruction, exhibit less “limp”, and can perform key activities of daily living such as shopping and collision avoidance. The importance of these data is that clinicians can now inform patients about potential outcomes using meaningful and tangible terms.

Contextualising 3D gait analysis for patients

The 3D gait analysis indicated a significantly better GPS score in functional reconstruction than in non-functional patients, exceeding known Minimal Clinically Important Differences (MCID) of 1.6 for GPS.¹⁶ The advantage of the GPS is that it is an objective measure that can be standardized to data from other studies.^{10,11} A normal control has a mean GPS of 5.4, a below knee amputation (BKA) wearing prosthetics has a GPS of 7.1, and an above knee amputation (AKA) has a GPS of 10.7.^{10,11} Therefore to contextualise the GPS score for patients, a functional reconstruction functions at a similar level to a patient with a BKA wearing prosthetics, whilst a non-functional reconstruction will be closer to an AKA. In real terms, this is a highly significant difference and is supported by the ‘huge’ effect size noted between groups. A significant difference was also noted in “step-time symmetry”, which in simple term means that there is perceptibly less “limp” in a patient’s gait after functional reconstruction.

Environmental Simulator Tasks

The Environmental simulator tasks provided answers to key patient questions regarding issues such as “Can I go shopping?” and “Can I go out on the street and be able to avoid bumping into people?” In this study, patients with a functional reconstruction could complete simulator shop-

Table 4 Patient-Reported Outcomes (TESS score)

	Patient	Follow-up interval	TESS (out of 100)
Functional	1	24	77.8
	2	9	71.8
	3	NR	NR
	4	66	81.02
	5	NR	NR
	6	24	68
	7	19	78.6
	8	22	64.2
	9	51	83.8
	10	48	94.6
	11	50	66.6
	12	14	66
	13	NR	NR
	14	21	72.6
	15	54	89
	16	22	88
	17	NR	NR
	18	12	96.8
	19	12	86.6
	20	12	81.4
	21	12	95.4
	22	15	88.2
	23	11	89.6
	24	21	97
Non-functional	25	NR	NR
	26	12	77
	27	24	78.6
	28	6	75.8
	29	NR	NR
	30	13	54.6
	31	24	71.4
	32	24	77.8
	33	12	63
	34	NR	NR
Mean of groups, significance		26.0 vs 16.4, p=0.18	81.85 vs 71.17, p=0.028

NR = not recorded (patients deceased or with metastatic disease at the start of PROMS data collection period, see Flowchart 1)

ping tasks and collision avoidance without a significant slowing in their normal walking speed. This means that patients can return to activities such as shopping or walking in a crowded street without hesitancy, undue caution or stopping. Patients who did not have a functional reconstruction were not able to complete the weighted shopping bag task.

Patient-Reported Outcome Measures

The TESS score in this study was significantly better for patients with a functional reconstruction compared to non-functional patients. Until recently, the MCID had not been delineated for the TESS score, despite its use in many sarcoma studies as an outcome measure. Estimates for MCID for the TESS score are in the range of 4-11.6.¹⁷ The present study noted a difference in the TESS score of 10.68, which

would support the notion that the difference in scores seen in the present study is of functional relevance to patients.

Electromyography indicates co-activation of transferred muscles

Although hamstring transfers have been used for over a century in poliomyelitis, criticisms regarding the transfer of non-synergistic muscles still persist.¹⁸ EMG is critical to demonstrate that muscle transfers can function during the correct part of the gait cycle. These are the first data to demonstrate co-activation of the hamstrings and ipsilateral quadriceps during the gait cycle, as demonstrated by synchronisation with 3D gait assessment. Concerns regarding the use of non-synergistic transfers such as the hamstrings, although seemingly logical, are therefore unfounded.

“Internal brace” theory of transferred muscles

This study also provides answers to a longstanding and perplexing question as to why a relatively weak muscle transfer - when measured by MRC grade, straight leg raise or dynamometry parameters - can be effective for walking. Transferred muscles are postulated to work via an “internal brace” effect, with co-activation of transferred muscles with ipsilateral residual quadriceps demonstrated in stance phase during EMG testing. It is surmised that muscle transfers are thought to be at a mechanical disadvantage, with the knee in flexion. Once the patient is in the standing position, the vector of pull changes to allow a transferred muscle to “lock” the knee during the stance phase of gait. This therefore may act like an internal “dynamic brace” during the gait cycle, thereby allowing even a relatively weak transfer (as measured by MRC grade) to be effective in the “stance” position. This further emphasizes the need to measure objective functional parameters rather than non-functional assessments such as MRC grade or knee extension strength, particularly in mechanically disadvantaged positions (e.g., seated).

Algorithm for reconstruction

The Canniesburn Plastic Surgery Unit follows the algorithm described in 2012,¹⁹ which takes into account two factors: the degree of quadriceps resection and the associated soft tissue envelope defect. In brief, the long head of biceps femoris and sartorius transfers represented the primary choice in most cases, whilst free functional transfers were reserved for cases with a concomitant major soft tissue defect. The present study was not powered to examine differences in functional outcomes between surgical techniques, and therefore the preference for pedicled transfers remains a pragmatic one, given that free functional transfers take approximately 9 months to recovery function. A future revision of our algorithm will incorporate a third factor in determining choice of technique, placing greater emphasis on the need for endoprosthetic cover irrespective of degree of quadriceps resection.

Bias, Limitations and Generalisability

In sarcoma, heterogeneity in factors such as the degree of muscle resection may affect outcome measures such as TESS.²⁰ Selection bias exists in non-randomised trials, with surgeon preference potentially influencing patients chosen for functional reconstruction. However, both groups in this study were statistically equivalent for known functional parameters - extent of quadriceps resection, age, sex, radiotherapy and endoprotheses.²⁰ To further mitigate for differences in degree of muscle resection, data were re-analysed for patients with at least 2 quadriceps components resected, and the outcomes remained significant.

Additionally, time to testing dates were equivalent in both groups, and the use of a standardized surgical algorithm reduced variability in choice of surgical technique.

Data skewing may exist in 3D gait analysis as the study recruited fewer patients in the non-functional group. However, PROMs (completed by the entire eligible study cohort) supported the 3D gait analysis conclusions. Furthermore, 3D gait analysis did not sub-select a group of higher functioning patients as TESS scores in the gait analysis sub-group were similar to the group as a whole (Supplementary Digital Content 5). The use of an internationally accredited gait lab and validated sarcoma PROMs allows generalisability of this research to other major sarcoma units.

Summary

This study has provided for the first time - objective and clinically relevant data on the recovery of function after muscle transfers for quadriceps reconstruction. These data have changed our practice, with all patients undergoing quadriceps resection now offered a functional transfer. These data can also empower patients to make a more informed choices and consent by providing answers to key patient questions raised earlier regarding functional reconstructions:

1. **Patients with a functional reconstruction can walk better than those without** - 3D gait analysis demonstrates better overall gait and less perceptible "limp". A functional reconstruction is approximately equivalent to a BKA, whilst non-functional closer to an AKA.
2. **Patients can return to activities of daily living** - patients can perform shopping and collision avoidance tasks, without having to hesitate, slow down or stop. Without a functional reconstruction, patients may not be able to walk with shopping bags.
3. **Walking aids** - patients with a functional reconstruction are significantly less likely to use a walking aid, with none requiring long-term use of a knee brace or wheelchair.
4. **Patients may notice meaningful benefits from functional reconstructions** - PROMs exceed estimates for MCID in sarcoma.
5. **Transferred muscles function like neo-quadriceps** - EMG shows co-activation of transferred hamstrings with the ipsilateral residual quadriceps during the gait cycle.

Ethical Approval

Regional Ethics Committee (18/NW/0165) and site specific management approvals from Strathclyde University and WestMARC Centre obtained in line with Greater Glasgow and Clyde R and D board requirements. ClinicalTrials.gov identifier: NCT04911972.

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Patient Consents

Patient consents were obtained for the publication of identifiable photographs and videos.

Author contributions

Steven Lo: Inception, development, data collection, data analysis, writing manuscript, **Craig Childs:** development, data collection, data analysis, writing manuscript, **Ashish Mahendra:** development, data collection, writing manuscript, **Peter Young:** development, data collection, writing manuscript, **Bruce Carse:** development, data collection, data analysis, writing manuscript.

Conflict of Interest

The authors have no disclosures.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.bjps.2022.08.009](https://doi.org/10.1016/j.bjps.2022.08.009).

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