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Angle-specific analysis of knee strength deficits after ACL reconstruction with patellar and hamstring tendon autografts

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Abstract

After anterior cruciate ligament reconstruction (ACLR) there are differences in the neuromuscular deficits observed in patients with bone-patellar tendon-bone (BPTB) and with hamstring tendon (HT) autografts. Differences in knee extensor and flexor strength are commonly reported, but analyses have largely focused on peak torque metrics despite the requirement to generate torque through range when returning to sport. The aim of this study was to investigate the angle-specific strength and strength asymmetry differences between BPTB and HT around the time of return to play after ACLR. A total of 357 male field sport athletes with either a BPTB (n=297) or an HT (n=60) autograft underwent concentric knee flexor and extensor isokinetic strength testing nine months post-ACLR. Angle-specific torques were compared between grafts and limbs using 1D Statistical Parametric Mapping and discrete-point variables. Inter-limb extensor torque asymmetry was greater in BTPB than HT at knee angles of >30° (p=0.001, peak *d*=5.53), with flexor torque asymmetry lower in BPTB than HT at flexion angles of >25° (p=0.001, peak *d*=2.68). Angle of maximum asymmetry and angle of operated limb peak torque differed in knee extension for BPTB (p<0.001, *d*=0.32) but not HT, whereas knee flexion angle of maximum asymmetry and operated limb peak torque differed in both BTPB (p<0.001, *d*=0.75) and HT (p<0.001, *d*=0.43). Graft type affected extensor torque at knee angles of 67-85° and flexor torque at knee angles of 27-85°. Angle-specific strength analysis may inform the rehabilitation process and improve rehabilitation and return-to-play decision making strategies in comparison to the use of peak torque values alone.

1. Introduction

Strength testing is a common method of measuring neuromuscular function and inter-limb asymmetries after anterior cruciate ligament reconstruction (ACLR), and is often included in ACL return to play (RTP) testing protocols.[1, 2] Previous research has indicated that strength deficits and inter-limb asymmetries in the quadriceps and hamstrings muscle groups are associated with increased risk of re-injury after ACLR.[3-6] Furthermore, reduced quadriceps strength is associated with decreased lower limb control and altered movement strategies seen post-ACLR, which potentially contribute to ACL re-injury rates.[7, 8]

Isokinetic dynamometry has been demonstrated to be a valid and reliable measure of quantifying muscle strength and thus is frequently used in RTP strength assessment.[8-10] Concentric isokinetic testing is commonly performed at 60°/s for quadriceps and hamstrings after ACLR, and is used to assess both absolute strength metrics and inter-limb asymmetries.[8, 11, 12] Analyses of strength measures are typically focused on discrete-point metrics such as peak torque[13], despite the fact that non-contact ACL injuries[14, 15] and maximum tensile forces on the ACL[16] occur with the knee in more extended positions than the angle at which peak torque is achieved. Torques at specific angles of knee flexion have been shown to correlate more closely than peak torque with performance metrics in jumping and hopping tasks[17], and analysis of strength throughout the knee joint range may provide more relevant information about the athlete's rehabilitation status than peak torque values alone.[18]

Deficits in knee flexor and extensor peak torque after ACLR appear to be strongly influenced by the graft chosen to reconstruct the ACL. The two most commonly selected donor grafts are bone-patella tendon-bone (BTPB) and hamstring (HT) autografts, taken from the injured limb.[19] Each graft is associated with strength deficits related to the tissue harvest site: Deficits in knee extensor peak torque are greater following BPTB grafts and deficits in knee flexor peak torque are greater following HT grafts.[20] In addition, deficits have been reported for each graft type at angles other than the angle of peak torque. For example, greater extensor deficits have been reported for BPTB grafts at knee joint angles between 60-95°. [20] Flexor deficits have also been found away from the angle of flexor peak torque in HT grafts, but not in BPTB grafts.[21, 22] Despite this, peak torque asymmetry is commonly used for RTP decision making and no study has previously examined strength asymmetry through range after ACLR. A comprehensive assessment of torque through the full range of knee flexion angles, alongside inter-limb asymmetry metrics, would be highly informative to the rehabilitation process after ACLR and may facilitate more informed decision making than analysis of peak torque alone.

The primary aim of this study was to investigate the angle-specific knee torque and inter limb asymmetry differences between ACLR patients with BPTB and HT grafts 8-10 months after ACLR surgery, which is around the time when many athletes return to sport. The secondary aim was to investigate the difference between the angle of peak torque and the angle of greatest torque asymmetry for both BPTB and HT grafts. It was hypothesised that (i) the effect of graft type would be angle-specific, with knee extensor torque deficits in BPTB grafts and knee flexor torque deficits in HT grafts greater at more flexed knee angles; and (ii) the angle of greatest asymmetry would differ from the angle of peak torque for both BTPB and HT grafts.

2. Methods

Participants

A cohort of 409 male multidirectional field sports players who underwent ACLR with a BPTB or HT autograft between October 2013 and June 2019 were recruited from the caseload of two orthopaedic surgeons. The inclusion criteria were: Age 18-35, male, participation in a multi-directional field sport (e.g. rugby, soccer, Gaelic football and hurling), and having undergone isolated primary ACLR surgery using either a BPTB or HT autograft 8-10 months prior to testing. Those with previous ACL injuries (to either limb), multiple ligament reconstructions and/or meniscal repairs were excluded from the study. Informed written consent was obtained from all participants prior to testing. The study was conducted in accordance with the Declaration of Helsinki [23] and was approved by the hospital ethics committee.

[TABLE 1]

Testing procedure

Height and body mass were measured immediately prior to testing. All participants completed a warm-up consisting of a two-minute jog and five body-weight squats and then a clinical testing battery including jump and change of direction tests. Participants then underwent concentric knee extension and flexion strength testing, assessed at an angular velocity of 60°/s through the range 0-100° knee flexion (where 0° represents a fully-extended knee) in a seated position using an isokinetic dynamometer (Cybex NORM; Computer Sports Medicine Inc, Stoughton, MA, USA). High relative reliability and moderate absolute reliability have been found for this protocol using the Cybex Norm,[8, 11] and an angular velocity of 60° /s has been found to identify the greatest strength deficits in ACLR patients.[12, 22] The participants performed a warm-up set of five repetitions of knee extension and flexion, building up from 60% to 100% of maximal effort. After a 60 second rest period, the participants completed two maximal-effort sets of 5 repetitions, with 60 second rest period between each set. They were instructed to push and pull as hard and fast as possible against the resistance with verbal encouragement. The non-operated limb was tested first before repeating the procedure with the operated limb.

Data processing

Torque, angle and angular velocity data sampled at 100 Hz were exported from the isokinetic dynamometer. Data was extracted from the set with the single repetition that contained the highest peak torque value achieved across the two data collection sets, excluding the first and last repetitions to avoid any potential discontinuities in angular velocity at the start and end of sets. Torque data were gravity-corrected based on a static limb weight measurement as per manufacturer's guidelines and divided by body mass prior to analysis. All torque, angle and velocity data were filtered using a 4th order zero-phase low-pass Butterworth filter with a cut-off frequency of 5 Hz. Only isovelocity (>50°/s) data could be analysed to avoid inertial effects, so it was necessary to define a knee flexion angle range to use for analysis.[22, 24] The range 15°-85° was chosen to maximise the ability to interpret 'end-range' strength whilst minimising the amount of datasets excluded for which the target angular velocity was not attained across the defined range. A total of 52 datasets (12.7% of total cohort) did not achieve an angular velocity >50°/s across this angular range so were excluded from subsequent analysis, yielding a final cohort of 357 datasets). Data were linearly interpolated to 1° steps, i.e. a total of 71 data-points.

Peak torque values, the corresponding knee angles, peak torque asymmetry for extension and flexion in both graft type groups, and the angle of greatest inter-limb asymmetry were calculated for discrete-point comparisons between graft types. Inter-limb asymmetry was quantified for each group, using a modified limb symmetry index equation to allow interpretation of asymmetry direction[25]:

$$\text{Asymmetry (\%)} = 100 - \left(\frac{\text{Operated limb}}{\text{Non-operated limb}} \right) \times 100$$

Data analysis

Continuous waveform analysis was performed using the open-source 1D Statistical Parametric Mapping (SPM) MATLAB package (SPM1D,version 0.4.3, spm1d.org).
1D SPM independent t-tests were used to compare torque-angle waveforms between the BPTB and HT groups for both extension and flexion separately on the operated limb, and to compare inter-limb asymmetry between BPTB and HT groups.

Discrete point parameters were assessed for normality using the Shapiro-Wilk test and then analysed using Student's independent t-tests to compare the two graft type groups, as no evidence was found for violation of the normality assumption. The discrete points were peak torque, angle of peak torque, peak torque asymmetry, largest asymmetry in relative torque across entire range of motion, and knee angle at the instant of largest inter-limb asymmetry. To quantify the magnitude of these differences for both discrete-point and SPM analysis, Cohen's *d* standardised effect size (*d*) was calculated and interpreted using the following thresholds: $d > 0.2$ = small; $d > 0.5$ = moderate; $d > 0.8$ = large.[26] All statistical analyses were performed in MATLAB (R2015a, MathWorks, USA.) and statistical significance was accepted at $\alpha = 0.05$.

3. Results

[FIGURE 1]

[FIGURE 2]

[FIGURE 3]

[FIGURE 4]

[TABLE 2]

Inter-limb asymmetry

Inter-limb asymmetry in extension torque (Figure 1- upper panel) was lower in HT than in BTPB, specifically in the range of 30°-85° (Figure 1 – middle panel), with large effect sizes ($p < 0.001$, peak $d = 5.53$; Figure 1 – lower panel). Differences in inter-limb asymmetry for flexion (Figure 2 – upper panel) were identified between 25°-85° (Figure 2 – middle panel), with BTPB demonstrating lower asymmetry in comparison to HT with large effect sizes ($p < 0.001$, peak $d = 2.68$; Figure 2 – lower panel).

Discrete-point parameters

Peak torque and angle of peak torque for the operated and non-operated limbs in both HT and BPTB groups are reported in Table 2. Extensor peak torque was higher in HT than in BPTB (p = 0.03, d = 0.311) and flexor peak torque was higher in BPTB than HT (p = 0.007, d = 0.365). Inter-limb peak torque asymmetry differed between grafts for both extensors and flexors: BPTB grafts had larger inter-limb extensor asymmetry than HT (p < 0.001, d = 0.725); HT had larger inter-limb flexor asymmetry (p < 0.001, d = 0.411). The angle of extensor peak torque was smaller (i.e. the knee was more extended) for BPTB than for HT grafts on the operated side (p = 0.003, d = 0.383) and the angle at which the largest inter-limb asymmetry occurred differed between graft types for both extensors (p = 0.04, d = 0.328) and flexors (p = 0.003, d = 0.394).

Angle of maximum asymmetry and angle of operated limb peak torque differed in knee extension for BPTB ($p < 0.001$, $d = 0.32$) but not HT, whereas knee flexion angle of maximum asymmetry and of operated limb peak torque were different in both BTPB ($p<0.001$, $d=0.75$) and HT ($p<0.001$, $d=0.43$).

Angle-Specific Torque

The extension and flexion torque curves and results of the SPM analysis are shown in Figure 3 (upper panel) and Figure 4 (upper panel). A difference in operated limb knee extension torque between BPTB and HT groups was identified from 67°-85° knee flexion (Figure 3 – middle panel), with HT producing higher torque with a large effect size ($p = 0.014$, peak $d = 2.85$; Figure 3 – lower panel). Comparison of flexor torque between grafts (Figure 4 – upper panel) shows a difference from 27°-85° (Figure 4 – middle panel), with BTPB producing higher torque than HT with a large effect size difference throughout the whole range ($p = 0.001$, peak $d = 2.4$) (Figure. 4 – lower panel).

4. Discussion

The aim of this study was to evaluate the angle-specific isokinetic knee extension and flexion strength and strength asymmetry differences between athletes with BPTB and HT autografts nine months after ACLR. The main finding was that using SPM analysis highlighted graft specific differences in inter-limb asymmetry that was most pronounced at larger knee flexion angles for extension and flexion. The angle of peak torque was not representative of the largest inter-limb asymmetry through range. In addition, angle-specific torque differences were found. BPTB grafts exhibited a marked decrease in extensor torque at >67° compared to HT grafts, whilst during flexion, HT grafts exhibited decreased torque throughout range but especially at inner range (>75°) when compared to BPTB grafts. This study highlights the importance of assessing torque and inter-limb asymmetry throughout range after ACLR, as strength symmetry and thus rehabilitation status could be over-estimated if only peak torque differences are examined.

Effect of graft type on angle-specific knee extensor strength

Angle-specific inter-limb asymmetry in knee extension has not been previously reported. We observed a large difference between grafts which varied throughout range. Mean inter-limb asymmetry was 24% at peak torque in BPTB grafts whilst the mean of the largest asymmetry value throughout the range was 71%. In addition, HT grafts asymmetry was 11% at peak torque with the largest asymmetry being 49%. The difference between graft types demonstrates that inter-limb asymmetry may be under-estimated when reporting only peak torques. In addition, differences were identified between the angle of extensor peak torque and angle of largest inter-limb asymmetry in BPTB grafts. Whilst the absolute difference in angle is relatively small (52° vs 58°), the inter-limb asymmetry values associated with these angles are substantially different (47% difference). This difference was also not seen in HT grafts, where the angle of maximal asymmetry in extension occurred at a smaller angle (54° vs 51°). A difference of up to 47% in reported inter-limb asymmetry would be expected to have a considerable impact on a clinician's judgement of an athlete's rehabilitation status and decisions relating to RTP timing.

Angle-specific analysis of the knee extension torque curves demonstrated a deficit in the BPTB graft in comparison to the HT graft at knee angles >67°. Whilst no previous study has directly compared the two grafts types along the continuous torque-angle waveform using SPM, previous studies utilising specified angle intervals have demonstrated that the largest difference in knee extension strength has occurred at >50° knee flexion when compared to the operated leg or controls.[21, 22] These findings agree with previous literature demonstrating that harvesting of the BTPB graft has a detrimental effect on knee extensor strength at more flexed knee angles in comparison to HT grafts.[27-29] BPTB grafts have been shown to have higher level of patellofemoral pain observed in the post-operative period and up to 2 years later. [30-33] This increase in anterior knee pain is thought to increase the arthrogenic muscle inhibition of the quadriceps. As anterior knee pain has been shown to be more prevalent at more knee flexed angles it can be postulated that for these reasons we identify the angle-specific knee extension deficit in BPTB (>67°) and an increased inter-limb asymmetry at higher knee angles, which is not replicated in HT grafts. [34-36] The results of this study highlight the importance of individualisation of rehabilitation to target range-specific deficits in strength, in particular, quadriceps strength at higher knee flexion angles. Although both inter-limb and intra-limb compensations can occur during multi-joint sporting movements and functional tasks [37], increased asymmetry has been associated with reduced sporting performance.[38] Using angle-specific analysis could aid practitioners in monitoring strength at knee angles that correlate more closely with performance of sport-specific tasks, such as vertical jumping and single leg hopping, and improve RTP decision-making.[17] The relationship between these metrics and patient-reported outcome measures would also be a valuable area for future work.

Effect of graft type on angle-specific knee flexor strength

Our findings demonstrated greater deficits in knee flexion torque in HT grafts than BPTB grafts through range, with the largest deficits evident at 85° (Figure 4A). These results are consistent with previous research conducted on HT grafts that demonstrate generalised hamstring weakness that is highest at larger knee angles.[21, 22] Baumgart, Welling, Hoppe, Freiwald and Gokeler [22] used phase-specific SPM analysis over a reduced knee range of motion in 38 team sports athletes with hamstring graft ACL reconstructions, finding that the largest difference in knee flexion torque between operated and non-operated limbs occurred at >75° knee flexion. Results from our study would suggest that these finding are graft-specific and cannot be extrapolated to BPTB grafts, which have significantly less inter-limb asymmetry (10% vs 17%), improved torque throughout range and maximal asymmetry at a [39]more-extended knee angle than HT grafts. Significant differences in knee angles at the point of greatest knee flexion asymmetry were observed between graft types (Table 4). The BPTB group had highest asymmetry at less knee flexed angles than the HT group (47° vs 56°). For both BPTB and HT grafts, the angle of highest asymmetry was different to that of peak torque angle. These angles also represent completely contrasting inter-limb asymmetry values, which represents a 19% difference both graft types. Differences of this size have a significant impact on the clinician's judgement of RTP status and rehabilitation focus for the athlete, since 10% asymmetry is the commonly utilised criterion. [4] It can be postulated that the difference observed at higher knee flexion angles are due to the impairment that occurs when the semitendinosus and gracilis tendons are harvested for HT grafts. There is evidence of individualised levels of tendon regeneration and an over development of bicep femoris hypertrophy, with patients with reduced or no regeneration demonstrating the highest levels of knee flexor strength deficit.[39, 40] Furthermore, angle-specific knee flexor deficits at 70° and 90° have been demonstrated in athletes with reduced semitendinosus cross sectional area.[41] This would support why the largest inter limb deficits are observed at deeper knee flexion angles as the bicep femoris is in a mechanically disadvantaged position and thus has reduced force production whilst decreased hypertrophy and cross sectional area of the semitendinosus muscle mean that strength in this knee flexion angle is reduced.[42] Thus, inner-range knee flexor strength exercises focused on reducing inter-limb deficits at higher knee angles must be a priority to minimise the well-documented risk of hamstring injury after ACLR.[43]

The use of through range analysis of isokinetic knee extensor and flexor torque curves has shown significant differences in force production capabilities of ACLR limbs dependent on graft type, with increased graft-dependent inter-limb asymmetries and changes in peak torque values. Graft-specific differences still exist at the common RTP timepoint of 8-10 months post-surgery, and thus the practice of utilising only peak torque values when evaluating RTP status may overestimate strength symmetry throughout range. It is important to consider athlete-specific factors when designing rehabilitation programmes and determining appropriate timing for RTP. Here we highlight that graft-specific rehabilitation and assessment to address the deficits highlighted in this paper may be indicated. Athletes with BPTB autografts may warrant greater focus on knee extensor strength in larger knee flexion angles, whilst those with HT autografts may warrant greater focus on knee flexion strength in larger knee flexion angles to promote activity and strengthening of the semitendinosus muscle and avoid excessive reliance on the biceps femoris muscle.

Limitations

We were only able to analyse data within the isovelocity region of the angular range, in which the knee was extending or flexing at the target angular velocity. This meant that it was not possible to investigate differences in torque at knee angles smaller than 15° or greater than 85°: Torque measurement at these extremes of extension and flexion is likely to require isometric assessment. However, we were able to report findings from a 70° range of motion for both the extensors and the flexors, which is the largest range analysed to date.[22] Alternative processing options, such as averaging across multiple repetitions, may influence the values and reliability of the results obtained especially when comparing throughout range.[44] Although our analysis was restricted to concentric testing and to a knee angular velocity of 60°/s in order to preserve as much of the isokinetic range as possible, our process did result in the exclusion of 12.7% of the participant cohort. Similar analyses conducted at greater angular velocities might be expected to provide deeper insight into the deficits observed during sport-specific rapid extension and flexion movements. However, testing at greater angular velocities would further reduce the isovelocity region of the angular range, due to the time taken to accelerate the limb from stationary to the desired angular velocity at the start of each extension and flexion movement [22], so the insight gained by evaluating deficits across an extended angular range would be compromised. Similarly, assessing eccentric isokinetic testing could provide additional relevant information but is known to be associated with lower reliability, particularly at higher angular velocities. [1, 45-47] Furthermore, only male participants were included in this study. Sex differences in ACL injury risk factors and incidence rate have previously been reported [48], so our findings cannot necessarily be extrapolated to female athletes. Establishing the extent to which autograft type also affects post-ACLR strength and strength asymmetry in females is an important area for future research. A final limitation of this study was that both surgeons were from a single centre and both perform predominantly BPTB grafts. The clinical decision-making process for graft selection is not standardised between clinicians/centres and is typically influenced by surgeon preference and training [49, 50] so other factors influencing surgical decision-making may impact the generalisability of our findings.

5. Conclusion

In athletes after ACLR, angle-specific analysis of knee extensor and flexor torques can identify deficits in magnitude and angle that are not reflected in traditional peak torque analysis alone. Angle-specific neuromuscular strength deficits are found for the knee extensors after BTPB grafts and for the knee flexors after HT grafts, particularly at larger knee flexion angles. The post-ACLR assessment process should thus include quantification of these angle-specific deficits to facilitate targeted graft-specific rehabilitation. Angle-specific analysis of isokinetic torque is recommended in RTP testing and research to give a more comprehensive insight into the rehabilitation status of the athlete.

Perspective

This is the first study to compare angle-specific inter-limb strength asymmetries between BPTB and HT grafts. Our results have shown that there are significant angle-specific deficits that are not observed when utilising peak torque measures in isolation, and that significant asymmetries occur at angles not concurrent with the angle of peak torque. This analysis can highlight graft-specific deficits that can then be targeted by rehabilitation, which otherwise would be unidentified and potentially lead to increased re-injury risk. Therefore, we recommend the use of angle-specific torque analysis when testing knee flexion and extension strength post-ACLR to help inform the rehabilitation process and aid clinical assessment of athlete RTP status.

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Table 1. Cohort anthropometrics

Metric:	BPTB group (n = 297)			HT group (n = 60)			p	Entire group (n = 357)		
	Mean		SD	Mean		SD		Mean		SD
Age (years)	25	±	4	26	±	5	0.085	25	±	4
Mass (kg)	83.7	±	10.3	79.6	±	9.7	0.005	83.0	±	10.3
Height (m)	180.8	±	6.0	177.9	±	5.4	0.001	180.3	±	6.0

Table 2. Discrete-point parameters

Discrete point parameters:	Extension								Flexion							
	BPTB			HT			p	Effect size	BPTB			HT			p	Effect size
	Mean		SD	Mean		SD			Mean		SD	Mean		SD		
Peak torque (Nm/kg.100) :																
Operated limb	235	±	53	251	±	43	0.03	0.311	152	±	30	141	±	31	0.007	0.365
Non-operated limb	240	±	55	257	±	43	0.03	0.32	154	±	31	150	±	29	0.36	0.13
Knee angle at peak torque (°):																
Operated limb	52	±	16	58	±	14	0.003	0.383	61	±	13	64	±	15	0.27	0.225
Non-operated limb	52	±	15	54	±	12	0.21	0.138	61	±	14	62	±	13	0.5	0.072
Peak torque inter-limb-asymmetry (%)	24	±	19	11	±	11	<0.001	0.725	10	±	18	17	±	11	<0.001	0.411
Largest limb-asymmetry in relative torque across entire range-of-motion (%)	71	±	33	49	±	29	<0.001	0.68	29	±	16	36	±	18	0.004	0.428
Knee angle at point of largest inter-limb torque asymmetry (°)	58	±	21	51	±	23	0.04	0.328	47	±	23	56	±	22	0.003	0.394

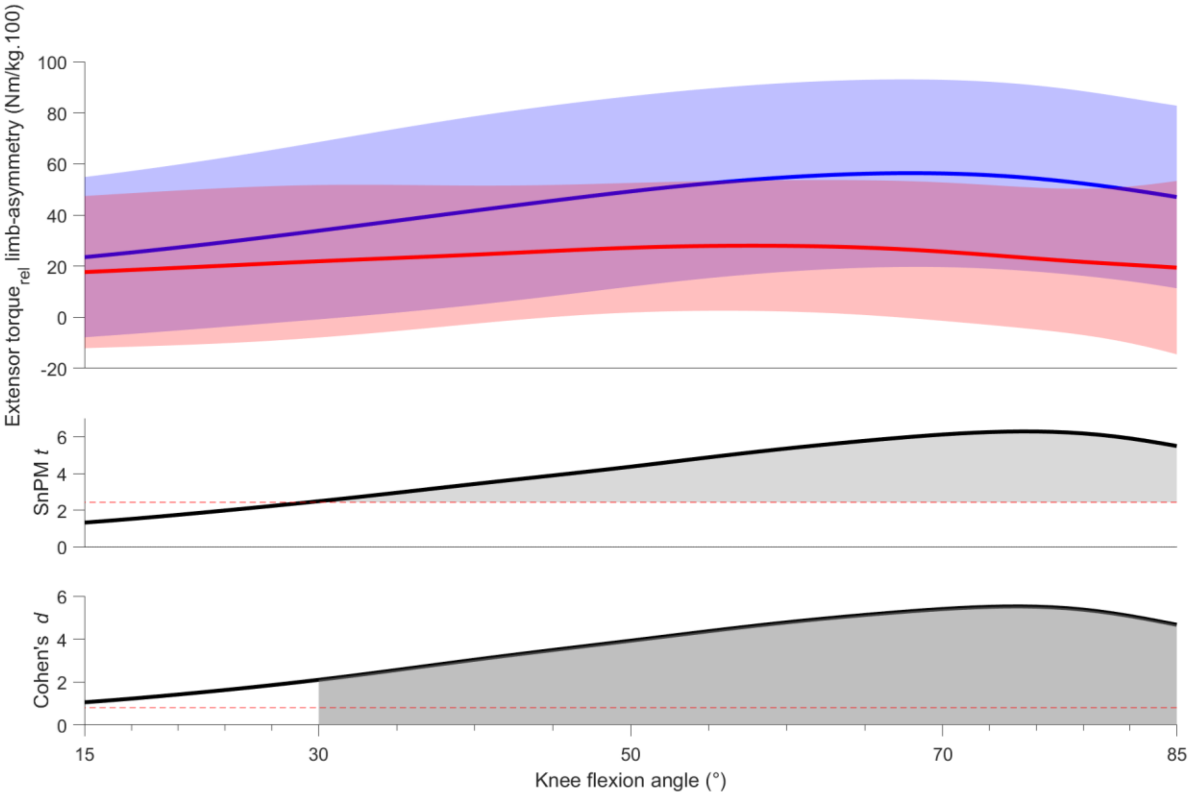

Figure 1 - Upper panel: Mean (solid line) and SD (cloud) of between-limb-asymmetry in extensor torque for the BPTB (blue) and HT (red) groups. The maximum difference in mean between-limb-asymmetry in extensor torque between the BPTB and HT groups is 31 Nm/kg, occurring at 75° of knee flexion.
Middle panel: t-statistic of SPM independent samples t-test comparing the between-limb-asymmetry in extensor torque between the BPTB and HT groups. Alpha level of 0.05, p = 0.001 and critical t-threshold of 2.43 (dashed red line), which is crossed at 30° until 85° of knee flexion. Shaded grey area corresponds to the segment of the range where critical t-threshold is crossed i.e. where there is a significant difference between groups.
Lower panel: Cohen's *d* effect size for the difference in between-limb-asymmetry in extensor torque between the BPTB and HT groups, with a maximum value of 5.53, occurring at 75° of knee flexion. BPTB group is reference value when calculating Cohen's *d* i.e. BPTB-HT. Dashed red line indicates 'large' effect size of 0.8. Shaded area corresponds to the segment of the range where there is a significant difference between both groups, as per SPM results.

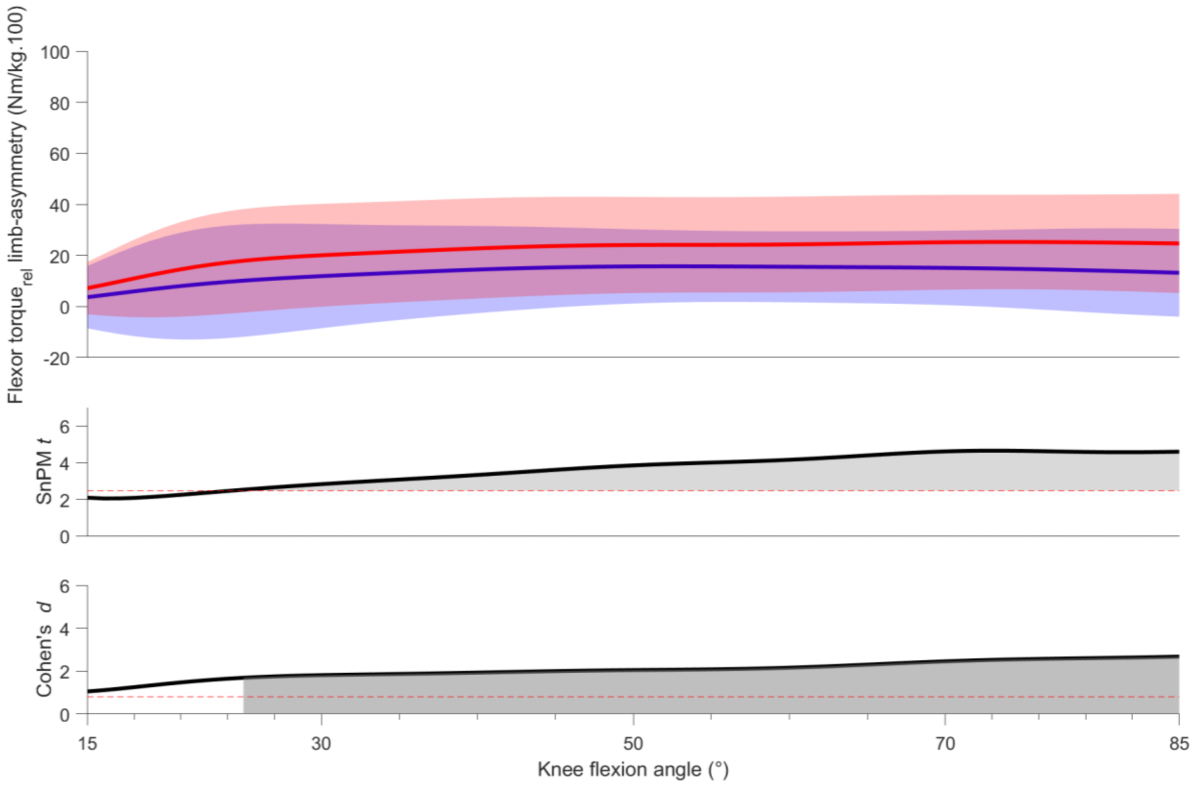

Figure 2 – Upper Panel: Mean (solid line) and SD (cloud) of between-limb-asymmetry in flexor torque for the BPTB (blue) and HT (red) groups. The maximum difference in mean between-limb-asymmetry in flexor torque between the BPTB and HT groups is 11 Nm/kg, occurring at 85° of knee flexion.
Middle panel: t-statistic of SPM independent samples t-test comparing the between-limb-asymmetry in flexor torque between the BPTB and HT groups. Alpha level of 0.05, $p = 0.001$ and critical t-threshold of 2.47 (dashed red line), which is crossed at 25° until 85° of knee flexion. Shaded grey area corresponds to the segment of the range where critical t-threshold is crossed i.e. where there is a significant difference between groups.
Lower Panel: Cohen's *d* effect size for the difference in between-limb-asymmetry in flexor torque between the BPTB and HT groups, with a maximum value of 2.68, occurring at 85° of knee flexion. HT group is reference value when calculating Cohen's *d* i.e. HT-BPTB. Dashed red line indicates 'large' effect size of 0.8. Shaded area corresponds to the segment of the range where there is a significant difference between both groups, as per SPM results.

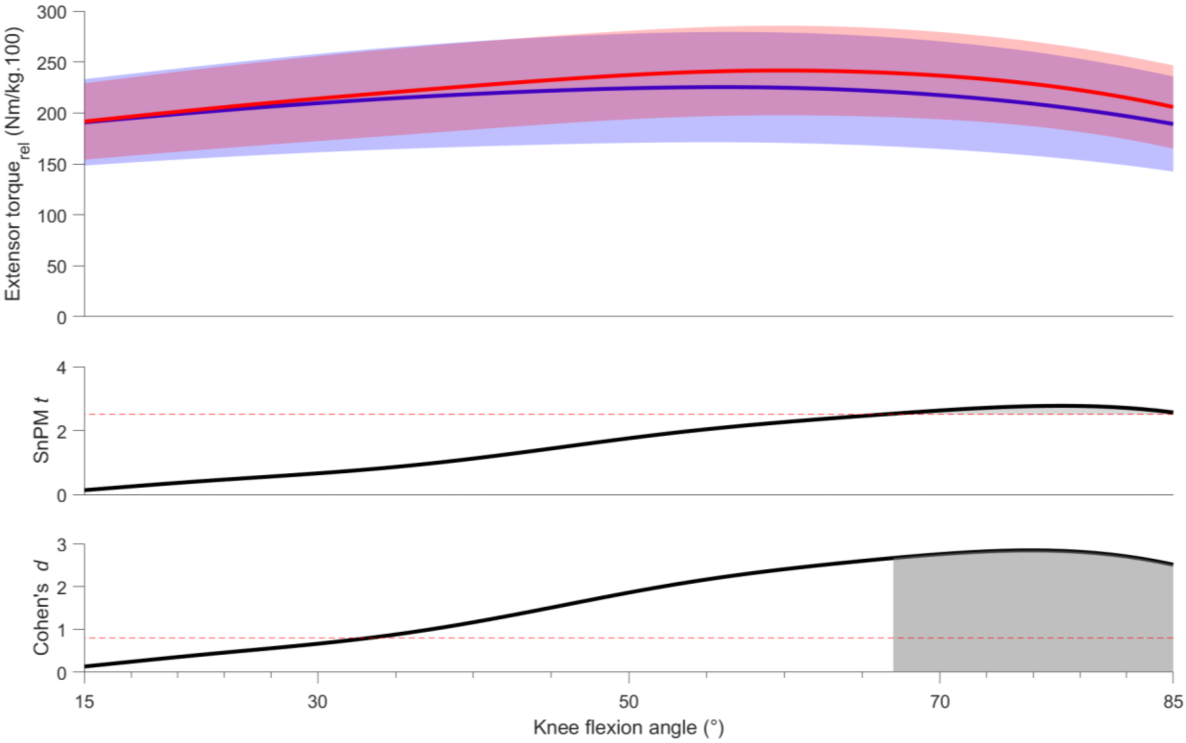

Figure 3 – Upper panel: Mean (solid line) and SD (cloud) extensor torque of the operated limbs of the BPTB (blue) and HT (red) groups. The maximum difference in mean relative extensor torque between the operated limbs of the BPTB and HT groups is 20 Nm/kg, occurring at 74° of knee flexion.

Middle panel: *t*-statistic of SPM non-parametric independent samples *t*-test comparing the extensor torque of the operated limbs of the BPTB and HT groups. Alpha level of 0.05, p = 0.014 and critical t-threshold of 2.51 (dashed red line), which is crossed at 67° until 85° of knee flexion. Shaded grey area corresponds to the segment of the range where critical t-threshold is crossed i.e. where there is a significant difference between groups.

Lower panel: Cohen's *d* effect size for the difference in relative extensor torque between the operated limbs of the BPTB and HT groups, with a maximum value of 2.85, occurring at 76° of knee flexion. HT group is reference value when calculating Cohen's *d* i.e. HT-BPTB. Dashed red line indicates 'large' effect size of 0.8. Shaded grey area corresponds to the segment of the range where there is a significant difference between both groups, as per SPM results.

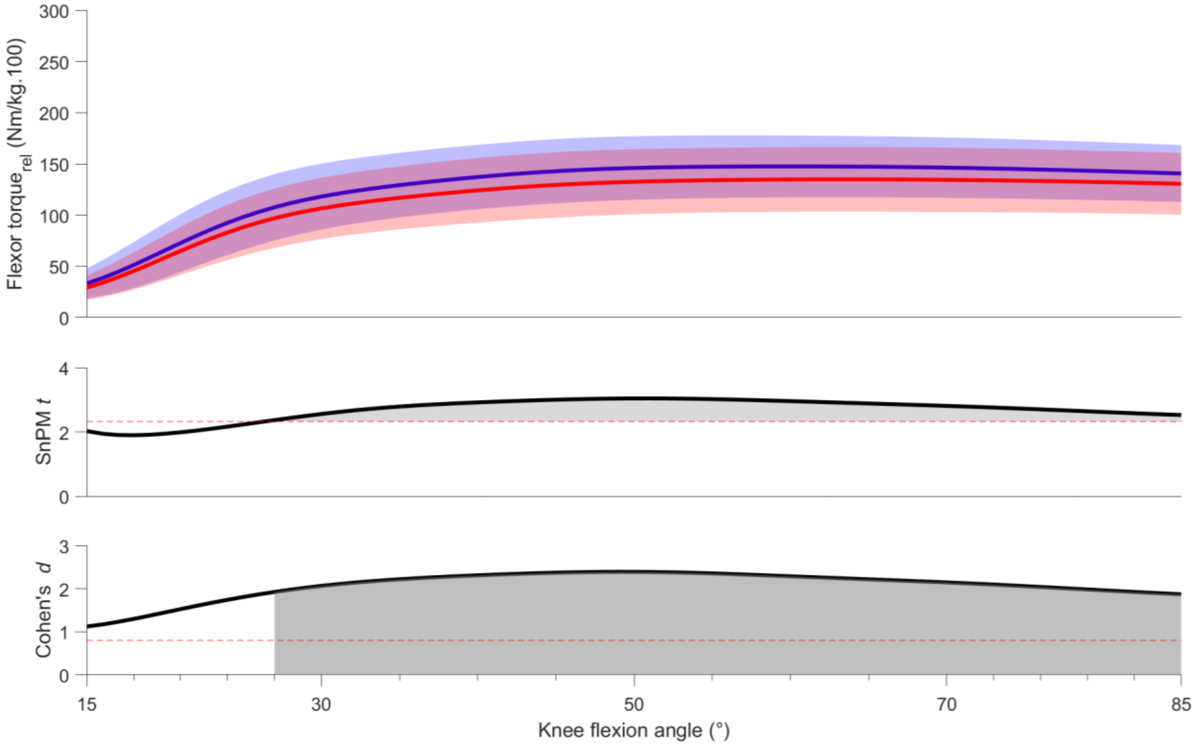

Figure 4 – Upper panel : Mean (solid line) and SD (cloud) flexor torque of the operated limbs of the BPTB (blue) and HT (red) groups. The maximum difference in mean relative flexor torque between the operated limbs of the BPTB and HT groups is 13 Nm/kg, occurring at 48° of knee flexion.

Middle panel: t-statistic of SPM independent samples t-test comparing the flexor torque of the operated limbs of the BPTB and HT groups. Alpha level of 0.05, p = 0.001 and critical t-threshold of 2.32 (dashed red line), which is crossed at 27° until 85° of knee flexion. Shaded grey area corresponds to the segment of the range where critical t-threshold is crossed i.e. where there is a significant difference between groups.

Lower panel: Cohen's *d* effect size for the difference in relative flexor torque between the operated limbs of the BPTB and HT groups, with a maximum value of 2.40, occurring at 49° of knee flexion. BPTB group is reference value when calculating Cohen's *d* i.e. BPTB-HT. Dashed red line indicates 'large' effect size of 0.8. Shaded area corresponds to the segment of the range where there is a significant difference between both groups, as per SPM results.