Citation:
Walker, J and Nicholson, G and Jongerius, N and Parelkar, P and Harris, N and Bissas, A (2020) Commonly reported isokinetic parameters do not reveal long-term strength deficits of the Triceps surae complex following operative treatment of Achilles tendon rupture. Journal of Biomechanics. ISSN 0021-9290 DOI: https://doi.org/10.1016/j.jbiomech.2020.109630

Document Version:
Article (Accepted Version)

COMMONLY REPORTED ISOKINETIC PARAMETERS DO NOT REVEAL LONG-TERM STRENGTH DEFICITS OF THE TRICEPS SURAE COMPLEX FOLLOWING OPERATIVE TREATMENT OF ACHILLES TENDON RUPTURE

Original Article

Josh Walker[1]*, Gareth Nicholson[1], Nils Jongerius[1,2], Parag Parelkar[1], Nick Harris[3], Athanassios Bissas[4]

[1] Carnegie School of Sport, Leeds Beckett University, Leeds, United Kingdom

[2] European School of Physiotherapy, Amsterdam University of Applied Sciences, Amsterdam, The Netherlands

[3] Spire Leeds Hospital, Leeds, United Kingdom

[4] School of Sport and Exercise, University of Gloucestershire, Gloucester, United Kingdom

***Corresponding author**

Carnegie School of Sport, Leeds Beckett University, Headingley Campus, Leeds, LS6 3QT, United Kingdom

Tel: +44 (0) 113 812 6822

Email: josh.walker@leedsbeckett.ac.uk

ABSTRACT WORD COUNT: 250 words

MAIN TEXT WORD COUNT: 3999 words

ABSTRACT

Isokinetic strength assessments are common outcome measures following operatively treated Achilles tendon (AT) ruptures. However, there is a lack of clarity on whether commonly reported outcome measures (such as peak joint moment) are sufficient to describe the extent of long-term functional deficits following AT rupture and repair. The present study conducted a comprehensive isokinetic evaluation of the Triceps surae complex in 12 participants who previously underwent AT rupture and repair. Testing occurred 4.4 (±2.6) years following surgery, and consisted of maximal isokinetic strength assessments of the plantarflexors at two angular velocities (30 and 60 $°\cdot s^{-1}$) with the knee in flexed and straight positions. Differences between injured and non-injured limbs were tested through discrete and statistical parametric mapping analysis. Average joint moment showed significant main effects between injured and non-injured limbs, but common isokinetic parameters such as peak moment and angle of peak moment did not. The normalised moment curves showed a significant main effect of limb, angular velocity and knee joint position on joint moment throughout different portions of the range of motion. Temporal analysis revealed a significantly greater ability of the non-injured limb to sustain plantarflexor moments across a range of testing conditions. Participants who had undergone operative treatment of AT ruptures did not display inter-limb differences in discrete isokinetic strength outcomes that are often used in the literature. Instead, temporal analyses were required to highlight the reduced capacity of the injured limb to generate end-range joint moments and to sustain higher levels of joint moment for longer periods.

KEYWORDS: strength, dynamometry, measurement, functional outcome, Achilles tendon

1.0 INTRODUCTION

Achilles tendon (AT) rupture is an injury that can have a profound and long-lasting impact on a patient’s functional capacity (Heikkinen et al., 2017; Horstmann et al., 2012). Both conservative and surgical treatment of AT ruptures is common although a lower incidence of re-rupture and quicker return to work has been reported for operative methods (Deng et al., 2017). Rehabilitation protocols that accompany these methods often differ in the weight-bearing load permitted (Eliasson et al., 2018). However, the ultimate goal of any approach is to return a patient to their former level of function by restoring strength levels and regaining an appropriate level of resting tension to the tendon. In any case, monitoring of patient progression is important to manage expectations and inform further decision-making processes. Whilst patient-reported instruments (e.g. Achilles tendon Total Rupture Score) (Nilsson-Helander et al., 2007) provide an indirect indicator of strength recovery, the use of an objective strength measurement should provide a more accurate measurement of patient progression. Therefore, it is not surprising that strength measurements utilising isokinetic dynamometry have been a common feature in many follow-up periods (Arslan et al., 2014; Bäcker et al., 2019; Leppilahti et al., 2000; Orishimo et al., 2018), which in part results from their capacity to test the ankle joint in isolation.

A challenge within the existing literature on isokinetic assessment following AT repair is the inconsistency in testing protocols employed and the parameters reported for post-repair assessments. This lack of consensus was confirmed emphatically in a very recent comprehensive review of strength measurement after AT repair, which revealed striking variability in the isokinetic protocols used in the literature (Bäcker et al., 2019). Of particular note was the range of angular velocities selected for testing (30 °·s^{-}1 to 180 °·s^{-1}), the variability in subject positioning (i.e. seated, supine, prone) and the range of knee flexion permitted. Given these factors have a clear impact on the force-velocity and length-tension relationships, and affect uni- and bi-articular muscle contributions to energy generation and transfer during plantarflexion, there is a concern whether a) measures obtained from existing tests provide surgeons and physiotherapists with a realistic evaluation of triceps surae strength after AT repair, and b) the clinical community has the necessary information to compare data from different studies and patients.

This limitation could be magnified in cases where only the peak joint moment (M_{peak}) is recorded. M_{peak} has been used extensively, and has been reported to differentiate between limbs with dissimilar strength levels following AT repair (e.g. Spennacchio et al., 2016). However, this discrete measurement alone may not be sufficient to elucidate the full long-term effects of the AT repair process as it captures only a single, although important, point of the moment-time curve. For instance, an examination of the time-series joint function throughout the range of motion (ROM) may add useful functional information on long-term deficits as generally daily and recreational activities are performed across a range of regions along the moment-time curve (King et al., 2017; Lai et al., 2015). Such indicators are crucial in fully understanding joint function and post-treatment progression, a fundamental requirement for decision-making by healthcare professionals. However, despite modern dynamometers offering access to a wide range of joint function indicators only few investigations (Borges et al., 2017; Heikkinen et al., 2017; Horstmann et al., 2012) have gone beyond the standard isokinetic parameters.

Another reason for examining beyond M_{peak} region is related with the changes in length that AT tendons may undergo following surgery. A known phenomenon occurring after AT surgery is tendon lengthening (Mortensen et al., 1991; 1999; Nyström & Holmlund, 1983), a change expected to affect the mechanical system (aponeurosis–tendon–moment arm) converting the triceps surae force into a moment. Indeed, a handful of investigations have reported a disproportionate weakness in end-range plantarflexion with no weakness apparent in M_{peak} following AT repair (Mortensen et al., 1999; Mullaney et al., 2006). Whilst these observations have been largely based on isometric measurements, it seems likely that end-range impairments in strength would theoretically affect stair descent, propulsion activities (i.e.

walking and running downhill) or landing from a jump. Despite these observed impairments, and the fact that M_{peak} occurs in the early stages of plantarflexion (Winegard et al., 1997), M_{peak} remains a common isolated parameter within clinical evaluations.

In addition to the weakness in end-range plantarflexor strength, tendon lengthening following AT rupture may also result in impairments in the rate of plantarflexor moment development as positive associations between tendon/aponeurosis stiffness and rate of moment development have been observed previously (Bojsen-Møller et al., 2005; Wilkie, 1949). Although recent investigations have provided evidence of compensatory morphological changes within the plantarflexors (e.g. reduction in resting fascicle length) in an attempt to regain pre-injury tendon tension (Baxter et al., 2018; Peng et al., 2017), there remains a lack of information regarding the influence of surgical treatment on the time-related characteristics of strength impairments following AT rupture.

Considering all the above factors, it becomes apparent that the existing voluminous literature on isokinetic strength measurements following AT rupture and repair also suffers from a persistence to univariate analysis, as well as inherent inconsistency due to dissimilarities in the testing protocols. This combination may prevent specialists to appreciate the full spectrum of strength characteristics post-surgery and agree which features could be more suitable for assessing recovery in different populations.

Therefore, there is a need to improve understanding of the ankle plantarflexors' function following AT repair and move towards an isokinetic assessment that provides robust information that is more functional and relevant to activities of daily living. This will enable us to identify the key mechanical parameters that more thoroughly explain any functional deficits, which may be hidden when conventional analysis is conducted. As such, the aim of this study was to conduct a comprehensive isokinetic evaluation of the Triceps surae complex in former patients who had undergone operative repair of an AT rupture. Based on mechanical concepts (such as length-tension and torque-velocity relationships) and previous research (e.g. Horstmann et al., 2012; Mullaney et al., 2006), it could be hypothesised that greater functional deficits will be observed in more plantarflexed regions of the range of motion in the injured limb. These deficits would be at a region different to the occurrence of M_{peak}, meaning it may add further information regarding the consideration of isokinetic testing. Additionally, taking isokinetic measurements at more than one angular velocity and in more than one knee position could reveal the effect of these manipulations on the outcome measures.

2.0 METHODS

Twelve participants volunteered for the current study (ten men, two women; age: mean 43.3 [standard deviation 3.6] years; stature: 1.74 [0.09] m; body mass: 80.2 [10.5] kg). These participants were part of an initial sample of 58 former patients of the same surgeon; two of these were omitted from potential participation due to contralateral injuries since initial AT rupture, whilst the remaining 44 did not volunteer to take part. The inclusion criteria required that participants a) had all previously suffered unilateral AT rupture, b) had undergone the same open surgical treatment by the same surgeon using the same materials (described in detail in Nicholson et al., 2019), and c) were prescribed the same post-operative rehabilitation program. The main exclusion criterion apart from the standard medical screening through the risk assessment process was history of another major lower limb injury, in the same or contralateral limb. The time since surgery of the participated cohort was 4.4 (2.6) years. All participants were healthy, engaging weekly in recreational physical exercise and provided informed consent before participation. The study received ethical approval from the local research ethical committee at Leeds Beckett University and was in accordance with the Declaration of Helsinki.

2.1 Testing protocol

Prior to testing, participants were required to abstain from any vigorous exercise for at least 24 hours. Participants underwent maximal concentric strength assessments of the Triceps surae muscle-tendon complex (MTC) using an isokinetic dynamometer (System 4 Pro, Biodex Medical Systems; NY, USA). Participants were placed in two testing positions: 1) seated with a hip angle of 65° (0° = full extension) and a fully extended knee joint (0°), and 2) seated with the same hip angle and the knee placed in 50° of flexion. The centre of rotation of the ankle joint, approximated using the lateral malleolus, was aligned with the axis of rotation of the dynamometer and the foot was secured to a footplate attachment using ratchet straps. Additional straps were placed over the thigh of the involved leg (to prevent any knee joint rotation) and across the pelvis (to restrict hip extension) ensuring isolation of the ankle joint in the intended plane of motion. In each testing position, isokinetic strength testing was carried out at two angular velocities (30 and 60 $°\cdot s^{-1}$) over three maximal repetitions. During each maximal effort, participants were instructed to plantarflex their ankle as “hard and fast as possible” (Maffiuletti et al., 2016) from peak dorsiflexion to peak plantarflexion. Prior to the maximal efforts, participants were provided with familiarisation repetitions, and rest periods of 90 s were allocated between sets. The order of testing side (injured and non-injured), knee position (straight and flexed) and angular velocity (30 and 60 $°\cdot s^{-1}$) were randomised. The knee joint positions were chosen to alter the relative contribution of the biarticular gastrocnemius muscle during plantarflexion whilst the two angular velocities were selected to differentiate between a high force and a more functional velocity (different portions of the force-velocity relationship), whilst still maintaining the ability to achieve a substantial isokinetic range for subsequent analyses (Iossifidou and Baltzopoulos,1996). These selections allowed a rigorous isokinetic testing at speeds very close to those achieved by healthy populations during common daily activities such as walking or stair ascent/descent (King et al., 2017). The fact that these knee positions and angular velocities also fall within the large range typically seen in AT rupture research (Bäcker et al., 2019) provides a degree of similarity so comparisons could be made with existing data. For each testing condition the joint moment, angle and angular velocity data were recorded (100 Hz) and extracted as raw digital signals for processing. Prior to testing in all conditions, a gravity correction was applied within the software to accommodate for the passive moment caused by the mass of foot and attachment.

2.2 Data processing

The best trial, defined as the trial that elicited the highest M_{peak}, from the three maximal-effort trials was taken forward for analysis. The start of the trial was defined as the first data point where the dynamometer began moving in a plantarflexion direction (positive angular velocity vector), whilst the end of the trial was defined as the final data point to have a positive angular velocity value (before it reached 0 $°\cdot s^{-1}$). Within the best trial, the isokinetic range was defined as the portion of data where angular velocity was within 5% of the target value to accommodate for any time delays in the dynamometer's feedback mechanism and noise in the angular velocity signal (Baltzopoulos, 2018). The time difference between the start of the trial and the start of the isokinetic range was termed "Acceleration Time", and the time difference from the start of the trial to M_{peak} was termed "Time to M_{peak}". These were the only values calculated using data outside of the isokinetic range.

Within the isokinetic range, several spatiotemporal variables were computed using a custom-written Matlab script (MathWorks, USA). The angle at which M_{peak} was achieved (θ_{peak}) was extracted for all best trials, as was average joint moment (M_{avg}). A θ_{peak} of 0° referred to a neutral ankle angle (i.e. in an anatomical standing position), negative values indicate dorsiflexion and positive values plantarflexion. The time duration participants were able to produce a joint moment above fixed percentages of M_{peak} were computed for both legs. These percentages ranged from 50% to 95% of M_{peak}, in increments of 5% ($T_{percent}$) with $T_{50\%}$ containing all the time spent between 50-100% whereas each consecutive level following this included the time from that particular level to 100% (e.g. $T_{85\%}$ = Time difference between 85-100%). These data provide context and more in-depth information around M_{peak} and infer high-moment work capacity of the Triceps surae MTC. Actual angular work done throughout the isokinetic range was calculated by the following equation:

$$W_{PF} = \int_{IR_{start}}^{IR_{end}} M_{PF} \cdot d\theta \tag{Eq. 1}$$

Where W_{PF} represents angular work (J), M_{PF} represents the plantarflexion joint moment (N·m), θ represents joint angle (rad), and IR_{start} and IR_{end} denote the start and end of the isokinetic range, respectively. M_{PF} during the isokinetic range for each best trial was normalised to a percentage of the isokinetic range of motion (0% = the first data point in the isokinetic range; 100% = the final data point in the isokinetic range), to provide continuous information of the injured and non-injured legs that can be directly compared.

2.3 Data analysis

A repeated measures three-way ANOVA (limb x position x angular velocity) was employed for most dependent variables to test main factor and interaction effects. A repeated measures two-way ANOVA (limb x position) was used for each velocity independently to test $T_{percent}$ values. Additionally, a statistical parametric mapping (SPM) repeated measures three-way ANOVA (limb x position x angular velocity) as described by Pataky (2010) was also performed using spm1d version M.0.4.5. in Matlab (MathWorks, USA) to compare differences in the normalised moment-angle curves between the injured and non-injured legs. SPM-type analyses are useful when comparing time-normalised n-dimensional biomechanical data. For a more-detailed explanation on the principles of SPM in this setting, see Robinson et al. (2015). In short, SPM uses a threshold (F-statistic for ANOVA) that is set at a specified alpha-level (usually 0.05). When the F-statistic exceeds this threshold, the null hypothesis is violated. Other statistical analyses were carried out using the Statistical Package for the Social Sciences (SPSS) software (version 24.0). For all statistical tests, alpha levels were set to 0.05.

3.0 RESULTS

Prior to comparisons between limbs, an independent velocity effect ($p<0.001$), regardless of limb and knee position, was noted for M_{peak} (30°·s^{-1} > 60°·s^{-1}). Similarly, independent velocity ($p<0.001$) and position ($p<0.05$) effects recorded for θ_{peak} with30°·s^{-1} and flexed knee producing their peak angles earlier into the movement. There were no significant differences in M_{peak}, θ_{peak} or W_{PF} between the injured and non-injured limb in all testing conditions (Table

1). However, there was a significant difference in M_{avg} between limbs across joint velocities and knee positions, with the injured limb being lower than the non-injured ($p<0.05$).

TABLE 1 HERE

There were no significant differences between limbs for the isokinetic range of motion, Acceleration Time or Time to M_{peak} in the straight or flexed knee conditions (Table 1).

For $T_{percent}$ variables, times were significantly longer at 30 $°\cdot s^{-1}$ in the non-injured limb from $T_{50\%}$ to $T_{80\%}$ ($p<0.05$; Figure 1) for both knee positions. Whilst the general trend was similar for the 60 $°\cdot s^{-1}$ condition, only the $T_{85\%}$ and $T_{90\%}$ levels reached significance, irrespective of joint position (Figure 1).

FIGURE 1 HERE

Main and interaction effects from SPM analyses have been shown in Figures 2 and 3, respectively. ANOVA results reveal no interaction effects of the normalised joint moment curve throughout the isokinetic range under all conditions (Figure 3). However, a main effect of angular velocity was shown between 1% and 37% ($p<0.001$), and 98% and 100% ($p=0.048$) of the isokinetic range with the 30 $°\cdot s^{-1}$ condition producing higher values (Figure 2A). A main effect of joint position from 88% to 100% of the isokinetic range was recorded with the flexed knee showing a higher joint moment in this region ($p=0.022$; Figure 2B). Finally, a main effect of limb was shown between 52% and 87% of the isokinetic range, with the non-injured limb displaying higher joint moments than the injured limb ($p<0.001$; Figure 2C; Figure 4).

FIGURE 2 HERE

FIGURE 3 HERE

FIGURE 4 HERE

4.0 DISCUSSION

The findings showed that basic isokinetic parameters (e.g. M_{peak}), commonly used to monitor strength outcomes following AT ruptures, were ineffectual to detect significant differences between injured and non-injured limbs. Instead, a more advanced analysis revealed time-series specific impairments in plantarflexor strength in the injured limb as well as a reduced capacity of the injured limb to sustain high levels of plantarflexor moment throughout an isokinetic ROM. Since these impairments may influence patients' efficacy in daily and sporting activities, the findings highlight the need to look beyond basic parameters when monitoring patient progression using isokinetic strength assessments.

Side-to-side plantarflexion strength deficits have been observed following operatively treated AT ruptures (Borges et al., 2017; Leppilahti et al., 1998; Maffulli et al., 2003), many of which have reported differences in commonly reported parameters such as M_{peak}, θ_{peak} or W_{PF}. In the present study, the absence of significant inter-limb differences in these parameters is therefore in disagreement with some studies. Several reasons could be suggested for this disparity including time since surgery, activity levels pre- and post-surgery, and variations in data collection techniques. A further explanation could be differing methods of treatment and rehabilitation (e.g. operative versus conservative treatment, open versus minimally invasive) between studies. This is one of the first studies to maintain consistency within the type of surgical procedure, the surgeon performing the operation and the rehabilitation protocol (Bevoni et al., 2014). This eliminates possible inter-surgeon technique variation and any inter-clinic post-surgery management that may exist in other studies.

M_{peak} in theory represents the peak capacity of the muscle group to generate joint motion. Although this parameter has previously been sufficient (e.g. Leppilahti et al., 2000) to differentiate between the injured and non-injured limbs, it corresponds to a single data point in the ROM and may lack some functional relevance to many daily tasks such as walking. Although M_{avg} was significantly lower (−16%) in the injured limb at 30 °·s^{-1} in the straight knee condition, it was the SPM analysis which revealed the time-series differences in strength between limbs with a main effect being observed at 52-87% of the isokinetic range (Figures 2C and 4). This is a key finding of the current study, as this range was notably beyond the region where M_{peak} occurred. This is in agreement with previous studies (Heikkinen et al., 2017; Mortensen et al., 1999; Mullaney et al., 2006; Orishimo et al., 2018) that have also shown end-range of motion strength deficits in the plantarflexors although many of these have been based on isometric assessments. Numerous explanations have been suggested to explain this impairment including selective plantarflexor inhibition, impaired force transmission through the tendon and excessive tendon lengthening (Heikkinen et al., 2017; Mullaney et al., 2006; Orishimo et al., 2018; Pajala et al., 2009). Whilst firm evidence in support of these remains controversial (Heikkinen et al., 2016; Kangas et al., 2007; Orishimo et al., 2018), it seems logical that greater muscle shortening allowed by tendon lengthening may change the portion of the length-tension relationship at which the tendon operates. Therefore, it is recommended that strength testing protocols incorporate conditions and/or parameters that provide information on strength throughout the ROM to assist in decisions regarding a patient's readiness to perform propulsive or landing-based activities, which place strain on the plantarflexors.

A novel aspect of the present study was the examination of the temporal characteristics of plantarflexor moment within strength assessments. No inter-limb differences in Acceleration Time or Time to M_{peak} were observed despite research showing a positive association between rate of moment development and tension within the muscle-tension complex (Bojsen-Møller et al., 2005; Wilkie, 1949). The reason for not observing differences in temporal characteristics may result from the compensatory remodelling (e.g. reduced fascicle length) that is known to occur within the Triceps surae to restore tendon tension to pre-injury levels (Peng et al., 2017;

Baxter et al., 2018), however such an explanation remains speculative without radiographic measures of muscle-tendon morphology.

Nevertheless, a unique finding of the present study was the significantly greater time that the non-injured limb was capable of sustaining joint moments above 50% of M_{peak} when tested over different angular velocities and knee positions (Figure 1). This is a concerning and interesting finding as it shows reduced capacity of the repaired MTC to withstand active loads for the same periods as the non-injured limb. Possible consequences of this phenomenon could involve asymmetrical behaviours of the two limbs when negotiating high external loads (e.g. stair climbing, loaded calf raises). In terms of explanations for the higher moment-work capacity of the non-injured limb, it is plausible that patients consciously reduced time under tension in the plantarflexors as a protective mechanism to avoid sustained periods of high stress. It is however more likely this impairment provides further support for the theory that tendon lengthening shifts the Triceps surae away from the optimal region of the length-tension relationship. That being said, there is an additional possibility that these explanations have a connection: the conscious effort to protect the AT has led to chronic reductions in the MTC work capacity. Although functional significance of this finding warrants future investigation, it further highlights the depth of information that can be gained from clinical strength examinations utilising isokinetic dynamometry.

Another unique aspect of this investigation was the testing of participants in a flexed and extended knee position across different angular velocities. Given the uni- and bi-articular nature of muscles within the Triceps surae complex, this approach was intended to allow differentiation between gastrocnemius and soleus interactions. Although significant inter-limb differences were more consistently observed for the straight knee position at 30 $°\cdot s^{-1}$, the flexed position may also offer insights of strength deficits between limbs. The use of the 60 $°\cdot s^{-1}$ speed can add information on the time-dependent strength capacities of limbs but employing 30 $°\cdot s^{-1}$ as the primary speed for investigations is recommended as, apart from its closeness to the joint's maximum strength capacity, it showed stability in detecting strength deficits for the injured limb. The main effect of knee joint position on ankle joint moment towards the end of the isokinetic range (Figure 2B) was an interesting and perhaps unexpected finding as it was the flexed knee position that elicited higher joint moments in this instance. Nonetheless, this finding does highlight the potential need for specificity in knee joint position during strength testing for this population. Given the variability in isokinetic protocols currently adopted by researchers and clinicians (Bäcker et al., 2019), the present findings provide medical professionals with a useful direction of how to streamline isokinetic monitoring procedures which are already time intensive.

This study was affected by some limitations. The study is retrospective and uses a within-subject design meaning the pre-injury level of asymmetry is not known, thus it is plausible that the non-injured limb may have undergone changes because of constraints imposed on the injured limb. Whilst only 12 of the initial sample (n=58) volunteered for testing, the standardisation of surgical methods, surgeon and rehabilitation pathway permitted the control of important confounding variables that are known to impact on patient outcomes. As such, the study provides novel information on isokinetic strength outcomes following AT ruptures that are treated and rehabilitated in a homogenous manner. Further research should include further biomechanical measurements of muscle function (e.g. electromyography or dynamic ultrasonography) during these movements to explore further some of the findings shown in the present study. Finally, the time since surgery at the point of testing was not controlled for in this study. Although this means the participants appear heterogeneous when it comes to time of recovery (mean 4.4 [2.6] years in the current study), significant limitations can be shown, depending on the chosen isokinetic protocol.

5.0 CONCLUSIONS

This study showed that patients who have undergone operative treatment of AT ruptures did not display differences in common isokinetic strength outcomes (e.g. M_{peak}). Instead, a more comprehensive analysis was required to highlight the reduced capacity of the injured limb to generate end-range joint moments and to sustain higher levels of joint moment for longer periods. The adoption of an isokinetic speed of 30 °·s^{-1} and positioning the knee in an extended position take priority over other testing conditions if testing time is limited. The present findings highlight the need for researchers and practitioners to look beyond basic isokinetic parameters when monitoring strength outcomes following AT rupture.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST STATEMENT

The named authors have no conflict of interest to disclose, financial or otherwise.

REFERENCES

1. Arslan, A. Cepni, S.K. Sahinkaya, T. May, C. Mutlu, H. Parmaksizoglu, A.S., 2014. Functional outcomes of repair of Achilles tendon using a biological open surgical method. Acta Orthopaedica et Traumatologica Turcica 48, 563-569.
2. Bäcker, H.C. Yenchak, A.J. Trofa, D.P. Vosseller, J.T., 2019. Strength measurement after Achilles tendon repair. Foot & Ankle Specialist 12, 471-479.
3. Baltzopoulos, V., 2018. Isokinetic dynanometry. In: Payton, C.J., Burden, A. (Eds.), Biomechanical Evaluation of Movement in Sport and Exercise (2nd Ed.). Routledge, Oxon, pp. 140-167.
4. Baxter, J.R. Hullfish, T.J. Chao, W., 2018. Functional deficits may be explained by plantarflexor remodeling following Achilles tendon rupture repair: preliminary findings. Journal of Biomechanics 79, 238-242.

5. Bevoni, R. Angelini, A. D'Apote, G. Berti, L. Fusaro,I. Ellis, S. Schuh, R. Girolami, M., 2014. Long term results of acute Achilles repair with triple-bundle technique and early rehabilitation protocol. Injury 45, 1268-1274.
6. Borges, P.R. Santos, T.R. Procópio, P.R. Chelidonopoulos, J.H. Zambelli, R. Ocarino, J.M., 2017. Passive stiffness of the ankle and plantar flexor muscle performance after Achilles tendon repair: a cross-sectional study. Brazilian Journal of Physical Therapy 21, 51-57.
7. Bojsen-Møller, J. Magnusson, S.P. Rasmussen, L.R. Kjaer, M. Aagaard, P., 2005. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. Journal of Applied Physiology 99, 986-994.
8. Deng, S. Sun, Z. Zhang, C. Chen, G. Li, J., 2017. Surgical treatment versus conservative management for acute Achilles tendon rupture: a systematic review and meta-analysis of randomized controlled trials. The Journal of Foot and Ankle Surgery 56, 1236-1243.
9. Eliasson, P. Agergaard, A.S. Couppe, C. Svensson, R. Hoeffner, R. Warming, S. Warming, N. Holm, C. Jensen, M.H. Krogsgaard, M. Kjaer, M., 2018. The ruptured Achilles tendon elongates for 6 months after surgical repair regardless of early or late weightbearing in combination with ankle mobilization: a randomized clinical trial. The American Journal of Sports Medicine 46, 2492-2502.
10. Heikkinen, J. Lantto, I. Flinkkilä, T. Ohtonen, P. Pajala, A. Siira, P. Leppilahti, J., 2016. Augmented compared with nonaugmented surgical repair after total Achilles rupture: results of a prospective randomized trial with thirteen or more years of follow-up. Journal of Bone and Joint Surgery 98, 85-92.
11. Heikkinen, J, Lantto, I. Piilonen, J. Flinkkilä, T. Ohtonen, P. Siira, P. Laine, V. Niinimäki, J. Pajala, A. Leppilahti, J., 2017. Tendon length, calf muscle atrophy, and strength deficit after acute Achilles tendon rupture: long-term follow-up of patients in a previous study. Journal of Bone and Joint Surgery 99, 1509-1515.

12. Horstmann, T. Lukas, C. Merk, J. Brauner, T. Mündermann, A., 2012. Deficits 10-years after Achilles tendon repair. International Journal of Sports Medicine 33, 474-479.
13. Iossifidou, A.N. Baltzopoulos, V. 1996. Actual angular velocity in eccentric isokinetic dynamometry. Isokinetics and Exercice Science 6, 65-70.
14. Kangas, J. Pajala, A. Ohtonen, P. Leppilahti, J., 2007. Achilles tendon elongation after rupture repair: a randomized comparison of 2 postoperative regimens. The American Journal of Sports Medicine 35, 59-64.
15. King, S.L. Vanicek, N. O'Brien, T.D. 2017. Sagittal plane joint kinetics during stair ascent in patients with peripheral arterial disease and intermittent claudication. Gait Posture 55, 81-86.
16. Lai, A. Lichtwark, G.A. Schache, A.G. Lin, Y.C. Brown, N.A. Pandy, M.G. 2015. In vivo behavior of the human soleus muscle with increasing walking and running speeds. Journal of Applied Physiology, 118, 1266-1275.
17. Leppilahti, J. Lähde, S. Forsman, K. Kangas, J. Kauranen, K. Orava, S., 2000. Relationship between calf muscle size and strength after Achilles rupture repair. Foot & Ankle International 21, 330-335.
18. Leppilahti, J. Forsman, K. Puranen, J. Orava, S., 1998. Outcome and prognostic factors of Achilles rupture repair using a new scoring method. Clinical Orthopaedics and Related Research 346, 152-161.
19. Maffiuletti, N.A. Aagaard, P. Blazevich, A.J. Folland, J. Tillin, N. Duchateau, J., 2016. Rate of force development: physiological and methodological considerations. European Journal of Applied Physiology 116, 1091-1116.
20. Maffulli, N. Tallon, C. Wong, J. Peng Lim, K. Bleakney, R., 2003. Early weightbearing and ankle mobilization after open repair of acute midsubstance tears of the Achilles tendon. The American Journal of Sports Medicine 31, 692-700.

21. Mortensen, N.H.M. Saether, J.A.I.N., 1991. Achilles tendon repair: a new method of Achilles tendon repair tested on cadaverous materials. The Journal of Trauma 31, 381-384.
22. Mortensen, N.H.M. Skov, O. Jensen, P.E., 1999. Early motion of the ankle after operative treatment of a rupture of the Achilles tendon. A prospective, randomized clinical and radiographic study. Journal of Bone and Joint Surgery 81, 983-990.
23. Mullaney, M.J. McHugh, M.P. Tyler, T.F. Nicholas, S.J. Lee, S.J., 2006. Weakness in end-range plantar flexion after Achilles tendon repair. The American Journal of Sports Medicine 34, 1120-1125.
24. Nicholson, G. Walker, J. Dawson, Z. Bissas, A. Harris, N., 2019. Morphological and functional outcomes of operatively treated Achilles tendon ruptures. Physician and Sportsmedicine, doi: 10.1080/00913847.2019.1685364.
25. Nilsson-Helander, K. Thomeé, R. Grävare-Silbernagel, K. Thomeé, P. Faxén, E. Eriksson, B.I. Karlsson, J., 2007. The Achilles tendon total rupture score (ATRS) development and validation. The American Journal of Sports Medicine 35, 421-426.
26. Nyström, B. Holmlund, D., 1983. Separation of tendon ends after suture of Achilles tendon. Acta Orthopaedica Scandinavica 54, 620-621.
27. Orishimo, K.F. Schwartz-Balle, S. Tyler, T.F. McHugh, M.P. Bedford, B.B. Lee, S.J. Nicholas, S.J., 2018. Can weakness in end-range plantar flexion after Achilles tendon repair be prevented?. Orthopaedic Journal of Sports Medicine 6, doi: 10.1177/2325967118774031.
28. Pajala, A. Kangas, J. Siira, P. Ohtonen, P. Leppilahti, J., 2009. Augmented compared with nonaugmented surgical repair of a fresh total Achilles tendon rupture: a prospective randomized study. Journal of Bone and Joint Surgery 91, 1092-1100.
29. Pataky, T.C., 2010. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. Journal of Biomechanics 43, 1976-1982.
30. Peng, W.C. Chang, Y.P. Chao, Y.H. Fu, S.N. Rolf, C. Shih, T.T. Su, S.C. Wang, H.K., 2017. Morphomechanical alterations in the medial gastrocnemius muscle in patients

with a repaired Achilles tendon: associations with outcome measures. Clinical Biomechanics 43, 50-57.

31. Robinson, M.A. Vanrenterghem, J. Pataky, T.C., 2015. Statistical parametric mapping (SPM) for alpha-based statistical analyses of multi-scale EMG time-series. Journal of Electromyography and Kinesiology 25, 14-19.
32. Silder, A. Heiderscheit, B. Thelen, D.G., 2008. Active and passive contributions to joint kinetics during walking in older adults. Journal of Biomechanics 41, 1520-1527.
33. Spennacchio, P. Vascellari, A. Cucchi, D. Canata, G.L. Randelli, P., 2016. Outcome evaluation after Achilles tendon ruptures. A review of the literature. Joints 4, 52-61.
34. Wilkie, D.R., 1949. The relation between force and velocity in human muscle. The Journal of Physiology 110, 249-280.
35. Winegard, K.J. Hicks, A.L. Vandervoort, A.A., 1997. An evaluation of the length–tension relationship in elderly human plantarflexor muscles. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences 52, B337-B343.

TABLE AND FIGURE CAPTIONS

Table 1. Means ± SD for M_{peak}, θ_{peak}, M_{avg}, W_{PF}, isokinetic range of motion, Acceleration Time and Time to M_{peak} in the different isokinetic testing conditions for the injured and non-injured limb.

Figure 1. $T_{percent}$ values (combined joint position [extended and flexed]) for the injured (solid line) and non-injured (dashed line) for both angular velocities. *, significantly different between limbs ($p<0.05$).

Figure 2. ANOVA statistics from SPM analysis, showing main effects for: (A) angular velocity, (B) knee joint position, and (C) limb (injured vs. non-injured).

Figure 3. ANOVA statistics from SPM analysis, showing interaction effects for: (A) limb x angular velocity, (B) limb x knee joint position, (C), angular velocity x knee joint position, and (D) limb x angular velocity x knee joint position.

Figure 4. SPM analysis for the combined normalised ankle joint moment curves for injured and non-injured limbs. ***, significantly different between limbs ($p<0.001$).

Figure 1

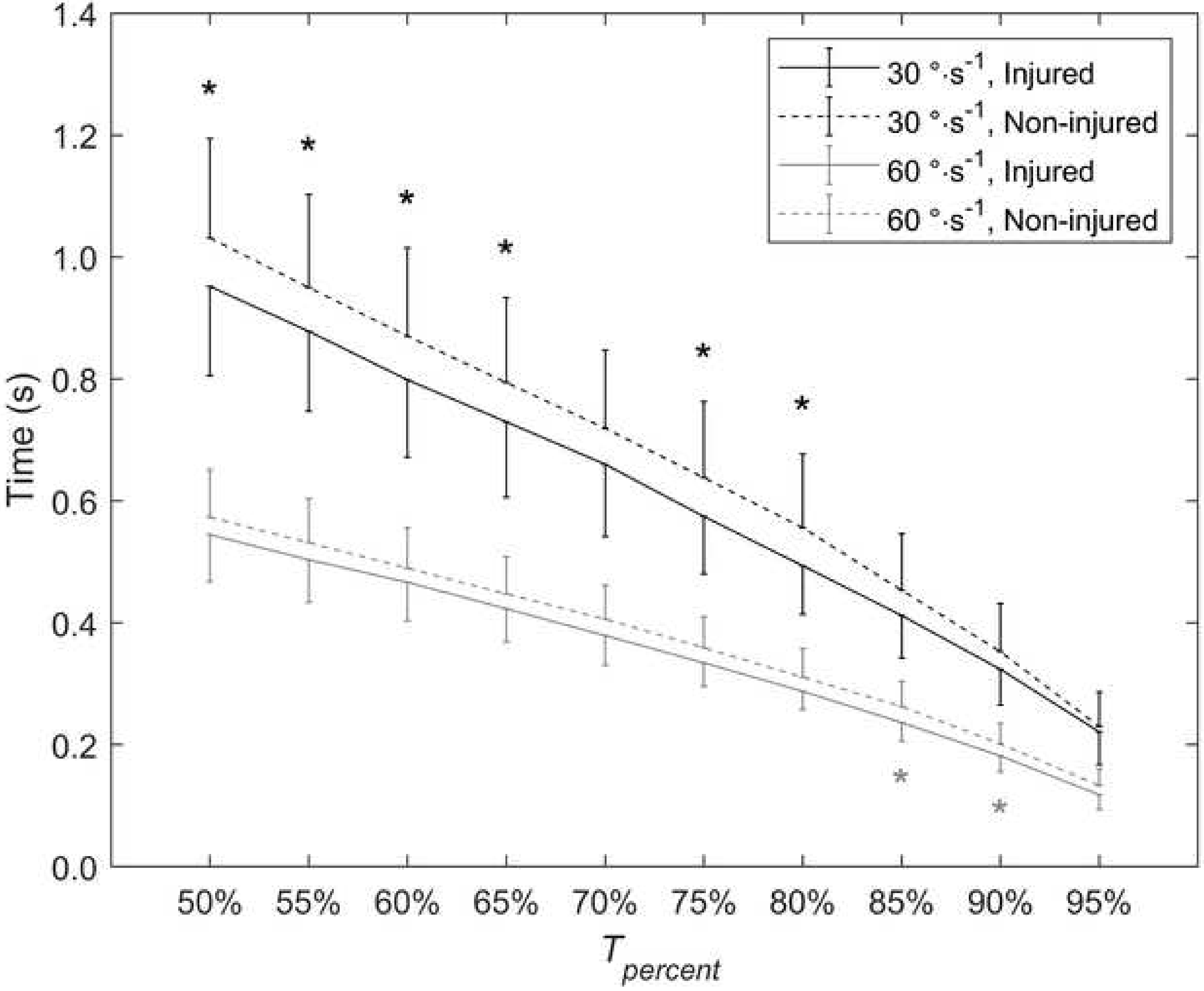

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Time (s)
50%
55%
60%
65%
70%
75%
80%
85%
90%
95%
$T_{percent}$
30 °·s-1, Injured
30 °·s-1, Non-injured
60 °·s-1, Injured
60 °·s-1, Non-injured
*

Figure 2

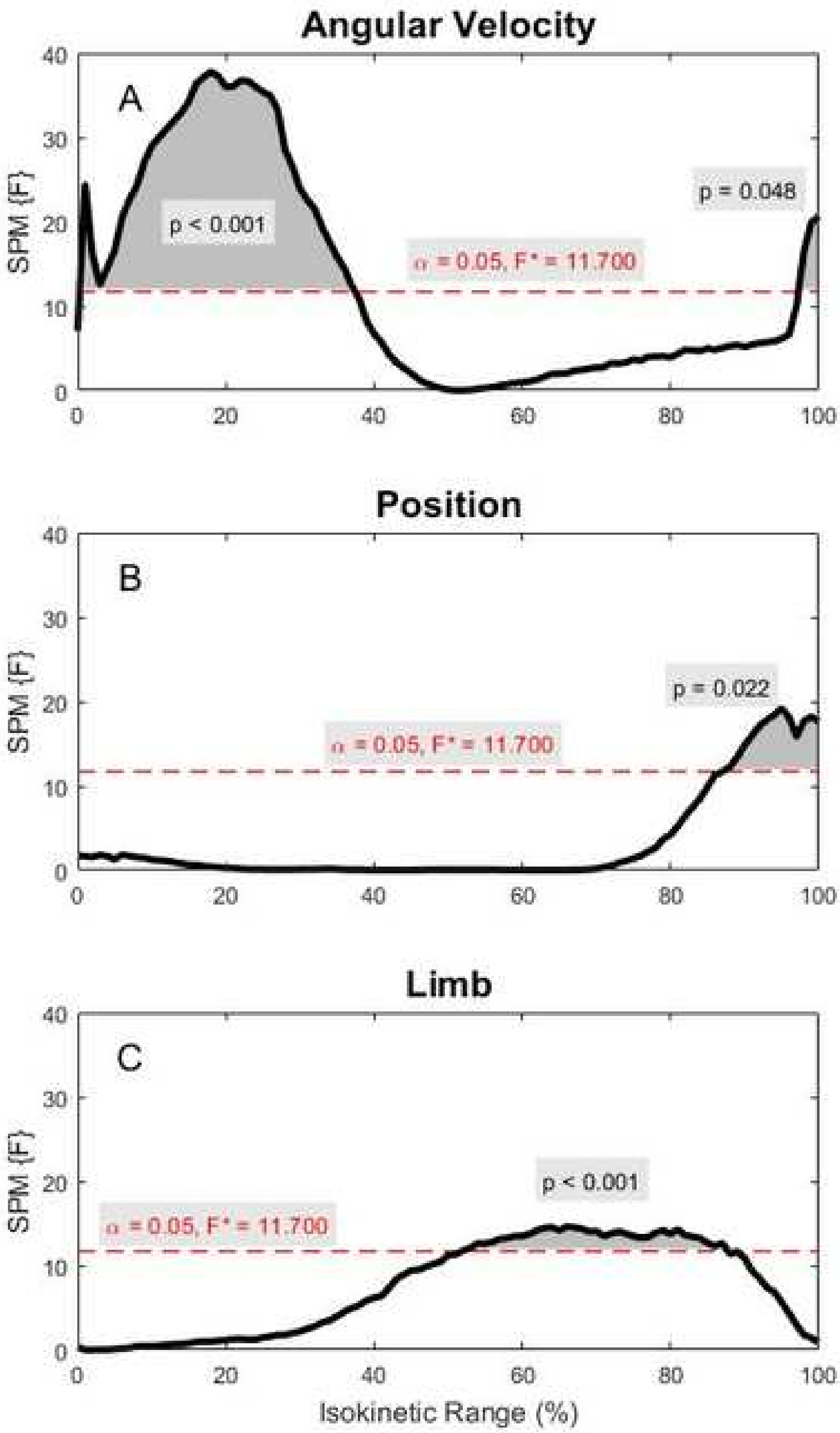
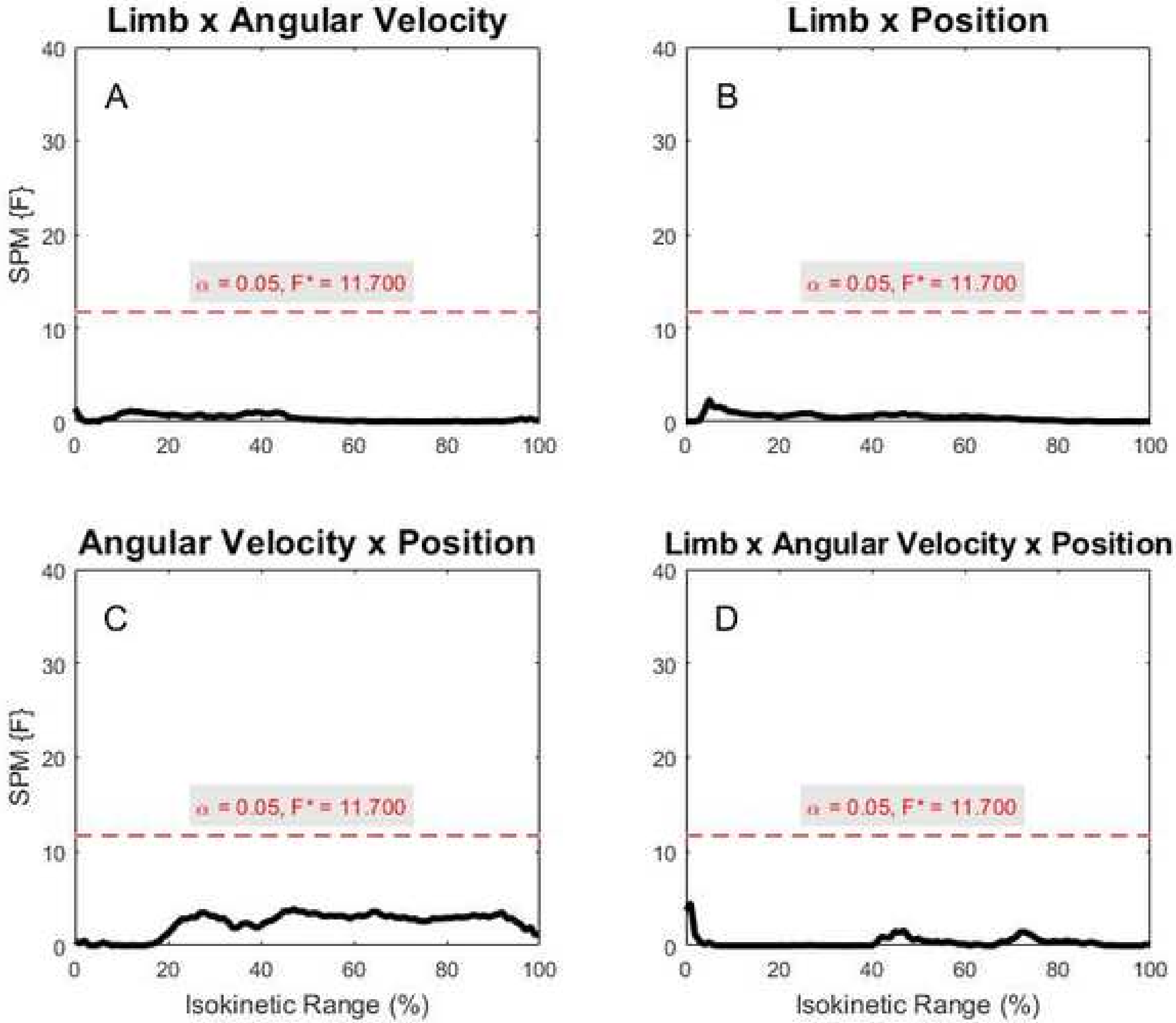

Angular Velocity
A
p < 0.001
p = 0.048
α = 0.05, F* = 11.700
SPM {F}
40
30
20
10
0
0
20
40
60
80
100
Position
B
p = 0.022
α = 0.05, F* = 11.700
SPM {F}
Limb
C
p < 0.001
α = 0.05, F* = 11.700
SPM {F}
Isokinetic Range (%)

Figure 3



Limb x Angular Velocity
A
Limb x Position
B
Angular Velocity x Position
C
Limb x Angular Velocity x Position
D
SPM {F}
SPM {F}
0
10
20
30
40
α = 0.05, F* = 11.700
α = 0.05, F* = 11.700
α = 0.05, F* = 11.700
α = 0.05, F* = 11.700
0
20
40
60
80
100
Isokinetic Range (%)
Isokinetic Range (%)

Figure 4

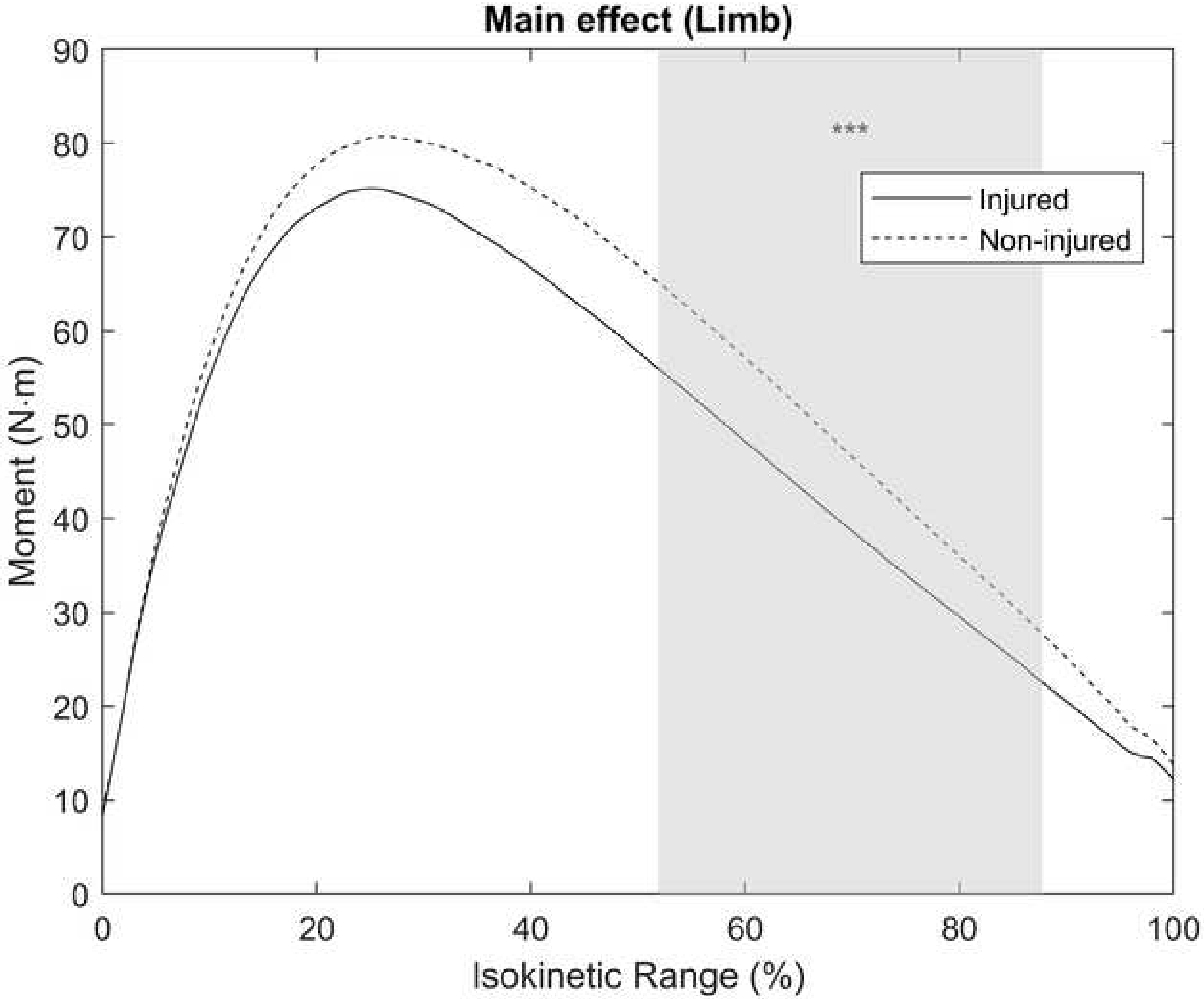

Main effect (Limb)
***
Injured
Non-injured
Moment (N·m)
0
10
20
30
40
50
60
70
80
90
Isokinetic Range (%)
0
20
40
60
80
100

Table 1

Position	**Straight knee (0°)**				**Flexed knee (50°)**			
Angular Velocity	**30 °·s^{-1}**		**60 °·s^{-1}**		**30 °·s^{-1}**		**60 °·s^{-1}**	
Limb	**Injured**	**Non-injured**	**Injured**	**Non-injured**	**Injured**	**Non-injured**	**Injured**	**Non-injured**
M_{peak} (N·m)	82.7±33.9	91.7±27.7	68.4±26.2	75.8±21.5	86.8±33.8	90.5±35.9	75.3±30.1	79.5±26.1
	ns		*ns*		*ns*		*ns*	
θ_{peak} (°)	3.1±5.8	5.3±5.7	4.9±7.5	7.9±4.6	−0.5±6.61	−0.1±7.8	3.0±6.7	3.1±7.7
	ns		*ns*		*ns*		*ns*	
M_{avg} (N·m)	48.6±19.0*	56.6±16.6	42.7±17.7*	49.4±14.9	50.5±20.3*	56.0±18.3	48.7±19.5*	52.4±16.4
	$p<0.05$		$p<0.05$		$p<0.05$		$p<0.05$	
W_{PF} (J)	44.1±20.2	50.1±18.3	39.5±16.6	44.0±16.0	42.6±18.0	48.4±21.3	41.4±16.3	45.1±16.8
	ns		*ns*		*ns*		*ns*	
Isokinetic range (°)	50.7±11.3	50.1±8.9	51.6±9.9	50.3±8.2	47.6±8.4	49.1±9.3	48.3±8.5	49.8±8.9
	ns		*ns*		*ns*		*ns*	
Acceleration Time (s)	0.07±0.05	0.08±0.09	0.06±0.02	0.06±0.03	0.09±0.05	0.08±0.04	0.05±0.02	0.08±0.06
	ns		*ns*		*ns*		*ns*	
Time to M_{peak} (s)	0.48±0.12	0.50±0.12	0.31±0.07	0.32±0.07	0.42±0.12	0.48±0.16	0.29±0.07	0.35±0.12
	ns		*ns*		*ns*		*ns*	

*significantly different from non-injured limb.

Conflict of Interest Statement

The named authors have no conflict of interest to disclose, financial or otherwise.

AUTHOR CONTRIBUTIONS

Josh Walker: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization. **Gareth Nicholson:** Conceptualization, Methodology, Formal Analysis, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Nils Jongerius:** Software, Formal analysis, Writing – Review & Editing, Visualization. **Parag Parelkar:** Methodology, Investigation, Writing – Review & Editing. **Nick Harris:** Resources, Writing – Review & Editing, Supervision. **Athanassios Bissas:** Conceptualization, Methodology, Writing – Review & Editing, Supervision.