The effect of fatigue on spike jump biomechanics in view of patellar tendon loading in volleyball

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Abstract

Background and objective

Patellar tendinopathy (PT) is a highly prevalent overuse injury in volleyball and is often linked with overloading of the patellar tendon. Little is known, however, about whether and how patellar tendon loading is affected by fatigue during the most challenging jump activity in volleyball. Therefore, this study investigates the effect of a high-intensity, intermittent fatigue protocol on movement alterations in terms of patellar tendon loading during a volleyball spike jump.

Methods

Forty-three male volleyball players participated in this study. Three-dimensional full-body kinematics and kinetics were collected when performing a spike jump before and after the fatigue protocol. Sagittal plane joint angles, joint work and patellar tendon loading were calculated and analyzed with curve analyses using paired sample t-tests to investigate fatigue effects ($p<0.05$).

Results

Fatigue induced a stiffer lower extremity landing strategy together with prolonged pelvis-trunk flexion compared to baseline ($p=0.001-0.005$). Decreased patellar tendon forces ($p=0.001-0.010$) and less eccentric knee joint work (-5%, $p<0.001$) were observed after the fatigue protocol compared to baseline.

Conclusion

Protective strategies seem to be utilized in a fatigued state to avoid additional tensile forces acting on the patellar tendon, including proximal compensations and stiff lower extremity landings. We hypothesize that players might be more prone for developing PT if eccentric patellar tendon loads are high in the non-fatigued state and/or these loads are somehow not decreased after fatigue.

Keywords

Jumpers knee, strain, exertion, biomechanics, stop-jump.

1. Introduction

Patellar tendinopathy (PT) is a common knee overuse injury in sports with repetitive bouts of jump-landing tasks. Volleyball players seem to be the most affected, with prevalence rates near 50% and incidence rates up to 30 injuries per 100 players per season.[1, 2] Symptoms of PT may vary from tenderness to pain or functional deficit, and might be aggravated when increasing the load on the knee extensor apparatus.[3, 4] As such, PT affects athletes' sports participation and might even disrupt their athletic career.[5] Therefore, understanding the risk factors and injury mechanisms of PT is necessary before developing effective prevention programs.[6, 7] Due to the multifactorial etiology of PT, there is a lack of strong evidence concerning extrinsic (e.g. activity volume) and intrinsic risk factors (e.g. body weight, jump height) for this condition.[6, 7]

Repetitive loading of the patellar tendon is considered to be an extrinsic risk factor for PT.[8] Accumulation of high eccentric tendon loading is thought to produce microtraumas to the tendon, which can eventually lead to intra-tendinous histopathological changes.[9] Moreover, tendon hysteresis levels (and subsequent intra-tendinous hyperthermia) are often related to loading patterns, although this is currently not confirmed for the patellar tendon.[10] Therefore, suboptimal tendon loading should be monitored carefully, certainly in case of non-uniform muscle-tendon adaptations (e.g. adolescent athletes).[11] Jump-landing biomechanics have the potential to detect risky movement patterns in terms of suboptimal patellar tendon loading.[9, 12, 13] Only three studies explicitly investigated patellar tendon loading during jump-landing tasks and found protective strategies including reduced peak patellar tendon forces and/or loading rate in subjects with current symptoms of PT.[8, 14, 15]

On the other hand, fatigue is considered to be a major extrinsic risk factor for knee injuries, primarily by modulating other intrinsic risk factors for lower extremity injuries such as jump-landing biomechanics.[16-20] Only one study investigated the effect of fatigue on patellar tendon loading in healthy basketball and soccer players and also found protective strategies with reduced peak patellar tendon forces after fatigue.[21] However, it remains unknown whether fatigue may modify PT injury risk in volleyball by altering patellar tendon loading during the most challenging jump activity in volleyball.

Therefore, the purpose of this study is to assess whether the execution of a volleyball spike jump changes when performing a fatiguing exercise in terms of patellar tendon loading. Full-body kinematics and kinetics during the entire landing phase will be assessed when performing a spike jump before and after a short-term fatigue protocol mimicking volleyball activities. Identifying full-body, fatigue-related biomechanical changes may provide new insight into the role of fatigue as a risk factor for PT.

2. Materials and Methods

2.1. Subjects

This study was registered at ClinicalTrials.gov (ID=NCT05161273), approved by the Ethical Committee of the Ghent University Hospital, and written informed consent was obtained from each participant. An a priori sample size of at least 33 players was estimated to observe a significant reduction in patellar tendon loading of 1.2 x body weight after fatigue (power=0.80, α=0.017 and d=0.76).[21] For inclusion, participants had to meet the following criteria: 1) male competitive volleyball players since PT is higher prevalent in this population[1], 2) at least 18 years old, and 3) at least 3 months free of injury and no history of PT. Since this study was part of a larger prospective cohort study examining fatigue-related biomechanical alterations predictive of PT, a convenience sample of 105 volleyball players was available to recruit from, which led to 43 participants meeting the selection criteria for the present study (age: 22.8±4.0 yr., weight: 79.5±10.6 kg, height: 184.0±7.5 cm, BMI: 23.5±3.0 kg/m², volleyball experience: 10.9±6.1 yr., volleyball participation: 6.7±1.9 hours/week).

2.2. Procedures

The test session started with a 10 minute standardized dynamic warm-up consisting of the familiarization with the fatigue protocol at self-selected speed without inducing any noticeable fatigue. Thereafter, three-dimensional biomechanics (kinematics and kinetics) were collected when performing spike jumps before and after the fatigue protocol. Between the baseline biomechanical testing and the fatigue protocol, subjects were asked to execute one circuit of the fatigue protocol at a low self-selected speed to ensure recovery and minimize potential fatigue induced by the baseline tests. All subjects wore their own indoor athletic shoes.

2.2.1. Spike jump

The spike jump was selected since it is a commonly performed jump maneuver in volleyball and also incorporates a horizontal landing phase, which induces a higher patellar tendon loading compared to jump-landings with a predominantly vertical landing component.[22] We focused solely on the participants' leading (dominant) leg during the horizontal landing phase since higher landing impact forces are assumed in this leg.[23] During the spike jump, subjects ran from a self-selected distance towards a volleyball net. Then, they landed with both feet separately on two force plates prior to pushing off vertically (horizontal landing phase). The force plates were located in front of the net, and the net was attached at a standardized height of 2.43 m. Jump height effort was standardized by asking to swing with the dominant hand forward to an imaginary ball positioned just above the net. Two practice trials were only allowed before the actual measurements during the baseline testing. Thereafter, subjects were asked to perform 5 valid spike jumps before and after the fatigue protocol. Spike jump trials were discarded if 1) one foot did not fully touch the force plate, 2) both feet did not touch the separate force plates, or 3) subjects were seen to show an adaptation in stride length in an attempt to target the force plates.

2.2.2. Fatigue protocol

A 5 circuit version of the high-intensity, intermittent exercise protocol (HIIP-5) was used to induce fatigue on the short term.[24] The HIIP-5 includes 5 circuits of exercises mimicking volleyball activities such as directional changes and jumps. The circuits were executed at the highest possible movement speed and each circuit was interspersed with passive rest periods of 30 seconds.[24-26] The HIIP-5 has been shown to induce acute and long-lasting responses in terms of elevated peak blood lactate and heart rate (HR) levels, and decreased jump height and maximal quadriceps muscle strength up to 30 minutes following completion of the protocol, assuring a sufficiently large time window for examining biomechanical parameters after fatigue.[24]

2.2.3. Data collection

To monitor fatigue, HR and rate of perceived exertion (RPE) scores were registered before and at the end of the HIIP-5. HR was registered using a Polar heart rate system (Polar, Electro, Finland) and can be considered a physiological marker for cardiovascular stress induced by the protocol.[27] Perceived physical effort was measured by means of a subjective RPE score for breathlessness (RPE-B) and legs (RPE-L) on a 20-point Borg scale.[28] Additionally, circuit time and overall protocol completion time was registered during the HIIP-5 with infrared timing gates (Microgate, Groningen, The Netherlands).

Kinematic data were collected with a 12 camera opto-electronic system (Oqus 3+, Qualysis, Sweden, 300 Hz) and synchronized with kinetic data gathered by 2 force plates embedded in the floor (AMTI, USA, 1200 Hz). Reflective markers were placed on the skin according to the ‘Liverpool John Moores University Lower Limb and Trunk Model’, which is reliable for measuring kinematics and kinetics during drop vertical jumps.[29] This eight-segment model defines the trunk, pelvis, upper legs, lower legs, and feet.

2.2.4. Data analysis

Kinematic and kinetic data were processed in Qualisys (Qualisys Track Manager, Qualisys, Sweden) and subsequently in Visual 3D software (Visual 3D v5, C-motion, Germantown, MD). Marker and force data were filtered using a fourth order Butterworth and critically damped low-pass filter at 20 Hz, respectively. Euler rotations (X-Y-Z) were used to calculate three-dimensional, full-body joint kinematics and kinetics. Since the spike jump is mainly a sagittal plane motion and (the main study outcome) patellar tendon loading is based on sagittal plane metrics, only sagittal plane data were utilized in this study. The horizontal landing phase was defined as the period from initial contact to take-off, which was determined using the vertical component of the ground reaction force with a threshold set at 25 N. For the kinematic data, joint angles were extracted for the pelvis relative to the trunk (pelvis-trunk), the thigh relative to the pelvis (hip), the shank relative to the thigh (knee) and the foot relative to the shank (ankle). Spike jump height was calculated based on the difference between the maximal vertical height of the pelvic segment during the flight phase of the spike jumps compared to the pelvic height during the standing static trial. For the kinetic data, patellar tendon forces were calculated by dividing the net knee joint moment by the patellar tendon moment arm, estimated as a function of the knee joint angle based on the method of Herzog and Read.[30] In case of negative patellar tendon forces, this was not interpreted as such. Eccentric (negative, from initial contact to peak knee flexion) and concentric (positive, from peak knee flexion to take-off) joint work was extracted by integrating the joint power curve. Overall joint work was calculated by the sum of the hip, knee and ankle joint work, and for each joint, the relative contribution to the overall joint work (ratio) was calculated. All kinetic data were normalized to body weight. After verifying that contact time during horizontal landing phase was not affected by fatigue (p=0.950, d=0.10), kinematic and kinetic data were normalized to 100%. Ultimately, this resulted in an average time profile before and after the HIIP-5, which were subsequently exported for statistical analysis.

2.2.5. Statistical analysis

The statistical analysis of the discrete outcome variables was performed in the software package IBM SPSS statistics 28. Biomechanical curves, i.e. normalized temporal profiles, were analyzed in Matlab (MathWorks, Inc., Natick, MA, USA) using Statistical Parametric Mapping (SPM, www.spm1d.org).[31] For all discrete outcome variables, normality was first checked with the Shapiro-Wilk test and corresponding normality plots. Thereafter, paired sample t-tests were performed with a Bonferroni correction for the number of executed tests within each cluster of outcome variables (fatigue variables: n=6, kinematics: n=4, joint work: n=8 and patellar tendon loading: n=3). Overall, the level of significance was set at $\alpha=0.05$. Effect sizes were calculated as Cohen's d (d) and classified as small (0.20-0.50), medium (0.50-0.80) and large (>0.80).[32]

3. Results

3.1. Fatigue variables

Fatigue variables are presented in Table 1. Overall HIIP-5 completion time was 5.7±0.3 minutes. Circuit time significantly increased from the 1st to the 5th lap. HR and RPE-scores significantly increased at the end of the HIIP-5 compared to pre. Spike jump height significantly decreased with 5% post-HIIP-5 compared to pre.

3.2. Biomechanical variables

3.2.1. Kinematics

Players performed the spike jump with significantly increased pelvis-trunk flexion from 59% to 94% of the entire landing phase post-HIIP-5 compared to pre (Figure 1A). Significantly decreased hip flexion was observed from 0% to 94% of the landing phase post-HIIP-5 compared to pre (Figure 1B). Knee flexion was also significantly reduced from 0% to 89% of the landing phase post-HIIP-5 compared to pre (Figure 1C). Finally, the foot was placed in a significantly more plantar flexed position from 5% to 14% of the landing phase and moved into significantly less dorsiflexion from 37% to 68% of the landing phase post-HIIP-5 compared to pre (Figure 1D).

3.2.2. Kinetics

3.2.2.1. Joint work

Overall and relative joint work are presented in Table 2 and Figure 2. Regarding overall joint work, no significant differences were found for eccentric joint work (Figure 2A), but 13% significantly less concentric joint work was observed post-HIIP-5 compared to pre (Figure 2B). Regarding relative joint work, the hip significantly worked 4% more during eccentric phase and 6% less during concentric phase post-HIIP-5 compared to pre (Figure 2C and 2D, respectively). The knee significantly worked 5% less during eccentric phase and 4% more during concentric phase post-HIIP-5 compared to pre (Figure 2C and 2D, respectively). To further illustrate the change in knee joint work, the profile of the knee joint moment against the corresponding knee joint angle was plotted (Figure 3). The figure shows less work during the eccentric phase of landing (green area) and more work during the concentric phase of landing (red areas) post-HIIP-5 compared to pre. No significant differences were observed for the relative eccentric and concentric ankle joint work post-HIIP-5 compared to pre (Figure 2C and 2D, respectively).

3.2.2.2. Patellar tendon loading

Patellar tendon forces were only interpreted between 12% to 95% of the landing phase since negative values were found (resulting from a knee flexion moment) from 0% to 12% and from 95% to 100% of landing. Patellar tendon forces generally decreased post-HIIP-5 compared to pre, which was significant from 12% to 32%, from 55% to 66% and from 87% to 89% of the landing phase (Figure 4A). Patellar tendon forces decreased as a result of decreased knee joint moments and higher patellar tendon moment arm lengths. As such, knee joint moments significantly decreased from 12% to 30% and from 88% to 89% of the landing phase post-HIIP-5 compared to pre (Figure 4B). Patellar tendon moment arm lengths significantly increased from 13% to 89% of the landing phase post-HIIP-5 compared to pre (Figure 4C).

4. Discussion

To the authors' knowledge, this is the first study that examines whether the execution of a volleyball spike jump changes when performing a fatiguing exercise in terms of patellar tendon loading. Overall, this study found significant, or a trend towards significant, decreased patellar tendon forces during the entire landing phase after fatigue.

In the past, decreased peak patellar tendon forces with a mean difference of 1.2 x body weight were also observed after fatigue during landing of a stop-jump task in basketball and soccer players.[21] Our study found decreased patellar tendon forces during the entire landing after fatigue, with a mean difference ranging between 0.0-1.0 x body weight. Interestingly, the highest difference was observed during the eccentric phase of landing. From a clinical point of view, decreased patellar tendon forces with 0.6 x body weight (95% CI=0.2-1.0) were observed along with patellar tendon pain decreases of 2.8 points (95% CI=0.3-5.3) on a visual analogue scale in subjects with current complaints of PT.[8] Although this study did not examine injured players and pain is not exclusively linked with tendon loading[33], the results of this study indicate that fatigue substantially decreased the magnitude of the patellar tendon force in healthy volleyball players, which might be a risk mitigating strategy against developing PT.

In order to reduce accumulation of patellar tendon loading in a fatigued state, both local and non-local strategies seem to be utilized. As a local strategy, reduced patellar tendon forces may be the consequence of reduced knee joint moments and/or increased patellar tendon moment arm lengths.[30] In this study, we observed both reduced knee joint moments and increased patellar tendon moment arm lengths. Stiff knee joint landings result in increased patellar tendon moment arm lengths[34], and are utilized in order to prevent the knee from collapsing during landing since players are unable to generate adequate knee extensor moments due to muscular fatigue.[21] Although stiff landings might increase knee 'safety', these may reduce players' ability to perform the spike jump, resulting in 5% less jump height and subsequently 4% relatively more concentric knee joint work as observed in this study. Non-local, proximal compensations may also reduce patellar tendon forces in the fatigued state. As such, the hip relatively worked 4% more to compensate the 5% decrease in knee joint work during the eccentric landing phase. In line with this, pelvis-trunk flexion was prolonged at the deepest point of landing. Proximal compensations are assumed to be essential for absorbing landing impact forces, certainly when stiffer distal joint behaviors occur.[12, 20] To conclude, it seems that volleyball players utilized both local and non-local adaptive strategies, including proximal compensations and stiff lower extremity landings, in order to reduce patellar tendon loading when fatigued.

Reducing patellar tendon loading when fatigued might decrease PT injury risk as it reduces cumulative microtraumas in the patellar tendon.[9] Interestingly, previous studies examining subjects with current complaints of PT demonstrated similar load-avoiding strategies in the 'fresh', non-fatigued state to limit pain, although there is currently limited evidence for this.[13, 15] Future high quality prospective cohort studies should explore whether players are more prone to develop PT if they exhibit high patellar tendon loads in the non-fatigued state and/or continue with eccentrically loading the tendon after fatigue. To illustrate this hypothesis, we determined PT injury risk profiles by dividing participants into 4 quadrants with color codes based on their change in peak patellar tendon loading and their change in spike jump height after fatigue (Figure 5). It was assumed that PT injury risk may increase when patellar tendon loading and/or jump height increases after fatigue. Besides that, those players with the highest non-fatigued patellar tendon loads (>Q75) are indicated as red dots. Our hypothesis would be that players situating in the yellow and red quadrants may be at the greater risk for developing PT, certainly when they are labeled with a red dot due to high patellar tendon loads in the non-fatigued state (>Q75). To further confirm our hypothesis, we compared subjective RPE-scores between the 4 quadrants and found no differences, suggesting that all players were equally fatigued and that increases in jump height may not be attributed to lower levels of fatigue. The question then arises whether fatigue-induced protective strategies are still possible during real-time competitive volleyball game play, when for example one may not have the option to jump less high. Current advances in markerless motion capture technologies seem to allow jump-landing related biomechanical evaluations on-field[35], hopefully soon making it possible to further develop and eventually test such hypothesis in prospective cohort studies.

The results of this study must be viewed within certain methodological limitations. First, jump height reduced with 5% after the HIIP-5 as a result of fatigue, although subjects were instructed to standardize jump height efforts during each spike jump. To still reach the target above the net, participants may have compensated with the head or arms which was not detectable with the biomechanical model that was used.[36] Decrements in jump height may also influence knee joint loads during landing in terms of decreased knee joint moments and joint work.[36] However, concentric knee joint work increased after fatigue, which could not be explained by jump height (as representation of total concentric work), as jump height decreased rather than increased with fatigue. Second, patellar tendon forces were calculated using the net knee joint moment, which did not take into account muscular cocontractions during landing. Previous research showed later peak muscular activity for the vastus lateralis, biceps femoris and medial gastrocnemius relative to the time of peak patellar tendon force after fatigue, which might have decreased peak patellar tendon forces.[21] However, decreased patellar tendon forces were observed during the entire landing phase of the spike jump in this study, illustrating that this did not influence our study results to a major extent. Third, this study only investigated sagittal plane biomechanics when estimating fatigue-induced alterations to patellar tendon loading. Future studies should explore in what way altered rotational tensile forces to the patellar tendon might increase PT injury risk.[12] Fourth, this study only included male participants since gender differences may affect (fatigue-induced) jump-landing biomechanics and PT prevalence is the highest for this population.[1, 37] However, the results of this study may not simply be extrapolated to the female population. Finally, this study did not examine whether between-subject differences in fitness levels (i.e. fatigability) had an impact on the research question of this study.[38] Only overall landing strategy adaptations were observed in this study, assuming that the HIIP-5 induces fatiguing effects irrespective of fitness levels.[24]

5. Conclusion

This study examined the effect of fatigue, induced by the HIIP-5, on spike jump strategy alterations and patellar tendon loading in volleyball players. The results showed that, when fatigued, protective strategies seem to be utilized in order to avoid additional tensile forces acting on the patellar tendon, including proximal flexed patterns and stiff lower extremity joint landings. We hypothesize that players might be more prone for developing PT if patellar tendon loads are high in the non-fatigued state and/or these loads are somehow not decreased after fatigue.

Perspective

Fatigue has recently been considered a candidate risk factor for lower extremity injuries in sports with repetitive bouts of jump-landing tasks such as volleyball.[16-20] Due to the repetitive accumulation of high impact loads in these sports, lower extremity overuse injuries such as PT are highly prevalent.[1, 12] However, it is currently not clear whether fatigue increases the risk for PT by altering biomechanics during the most challenging jump activity in volleyball. This study showed that, when fatigued, protective spike jump strategies seem to be utilized to have decreased patellar tendon loading, which may decrease the risk for developing PT. Although this was not yet investigated, we hypothesize that players who exhibit high eccentric patellar tendon loads in the non-fatigued state and/or somehow do not decrease these loads after a fatiguing exercise, might be more prone for developing PT due to the (over)production of cumulative microtraumas.[9]

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Table 1: Fatigue variables.

Fatigue variables	Pre (mean ± SD)	Post (mean ± SD)	Post-Pre (mean difference and 95% confidence interval)	Statistics (p-value and Cohen's d)
Circuit time (s)	42.1 ± 2.6	45.0 ± 4.1	+3.0 [+1.9, +4.0]	p<0.001*, d=0.88
Heart rate (bpm)	108.6 ± 14.0	190.9 ± 6.3	+82.3 [+77.8, +86.7]	p<0.001*, d=5.70
RPE-B (6-20)	7.8 ± 1.7	18.3 ± 1.6	+10.5 [+9.8, +11.2]	p<0.001*, d=4.46
RPE-L (6-20)	8.2 ± 1.9	15.6 ± 2.7	+7.4 [+6.5, +8.4]	p<0.001*, d=2.47
Spike jump height (cm)	61.5 ± 6.6	58.4 ± 6.0	-3.1 [-4.2, -2.1]	p<0.001*, d=0.94

Bpm = Beats per minute; cm = centimeter; RPE-B = Rate of perceived exertion for breathlessness; RPE-L = Rate of perceived exertion for legs; s = seconds. Significant results are indicated with an asterisk.

Table 2: Joint work before and after the HIIP-5.

Joint work		Pre (mean ± SD)	Post (mean ± SD)	Post-Pre (mean difference and 95% confidence interval)	Statistics (p-value and Cohen's d)
Eccentric	Overall (J/kg)	2.3 ± 0.7	2.2 ± 0.8	-0.1 [-0.2, +0.0]	p=1.000, d=0.21
	Hip (%)	8.0 ± 12.4	12.2 ± 12.4	+4.3 [+2.4, +6.2]	p<0.001*, d=0.71
	Knee (%)	74.7 ± 13.0	69.3 ± 12.4	-5.4 [-7.5, -3.4]	p<0.001*, d=0.81
	Ankle (%)	17.3 ± 5.6	18.5 ± 4.6	+1.1 [-0.0, +2.3]	p=1.000, d=0.30
Concentric	Overall (J/kg)	2.3 ± 0.5	2.0 ± 0.5	-0.3 [-0.4, -0.2]	p<0.001*, d=1.21
	Hip (%)	12.7 ± 12.4	6.8 ± 9.3	-5.9 [-8.6, -3.2]	p<0.001*, d=0.68
	Knee (%)	57.4 ± 9.7	61.9 ± 8.4	+4.4 [+2.3, +6.6]	p=0.001*, d=0.64
	Ankle (%)	29.9 ± 7.9	31.4 ± 7.0	-1.5 [-2.5, -0.4]	p=0.062, d=0.43

J = Joule, kg= kilogram. Significant results are indicated with an asterisk.

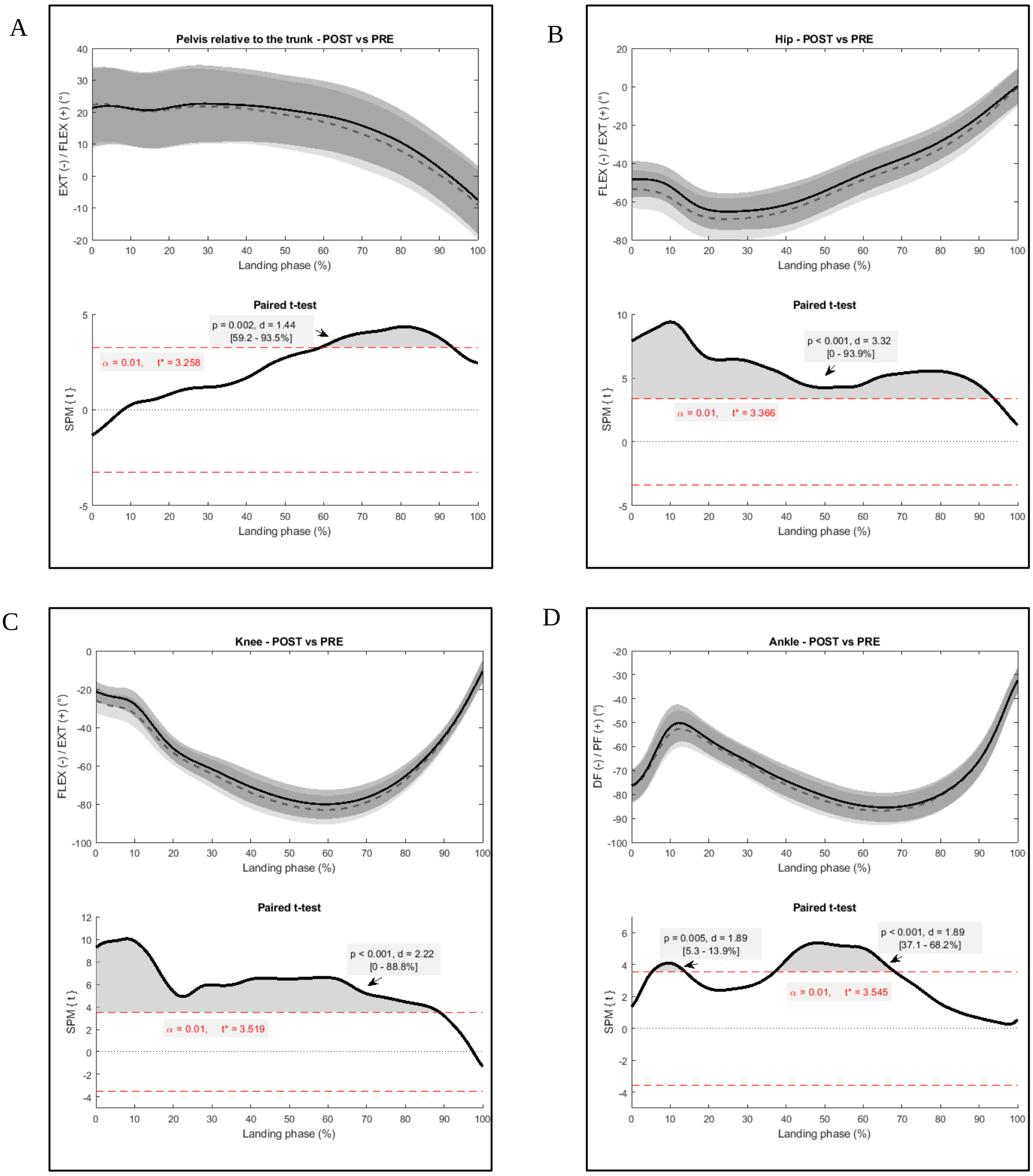

Figure 1: Full-body joint angles before and after the HIIP-5.

1A: pelvis-trunk, 1B: hip, 1C: knee, and 1D: ankle.

Kinematic trajectories are presented as mean and standard deviation clouds in the upper row (pre-HIIP-5: grey, dashed line; post-HIIP-5: black, solid line) and SPM inference results in the lower row ($p<0.05$).

DF = dorsiflexion; EXT = extension; FLEX = flexion; PF = plantar flexion.

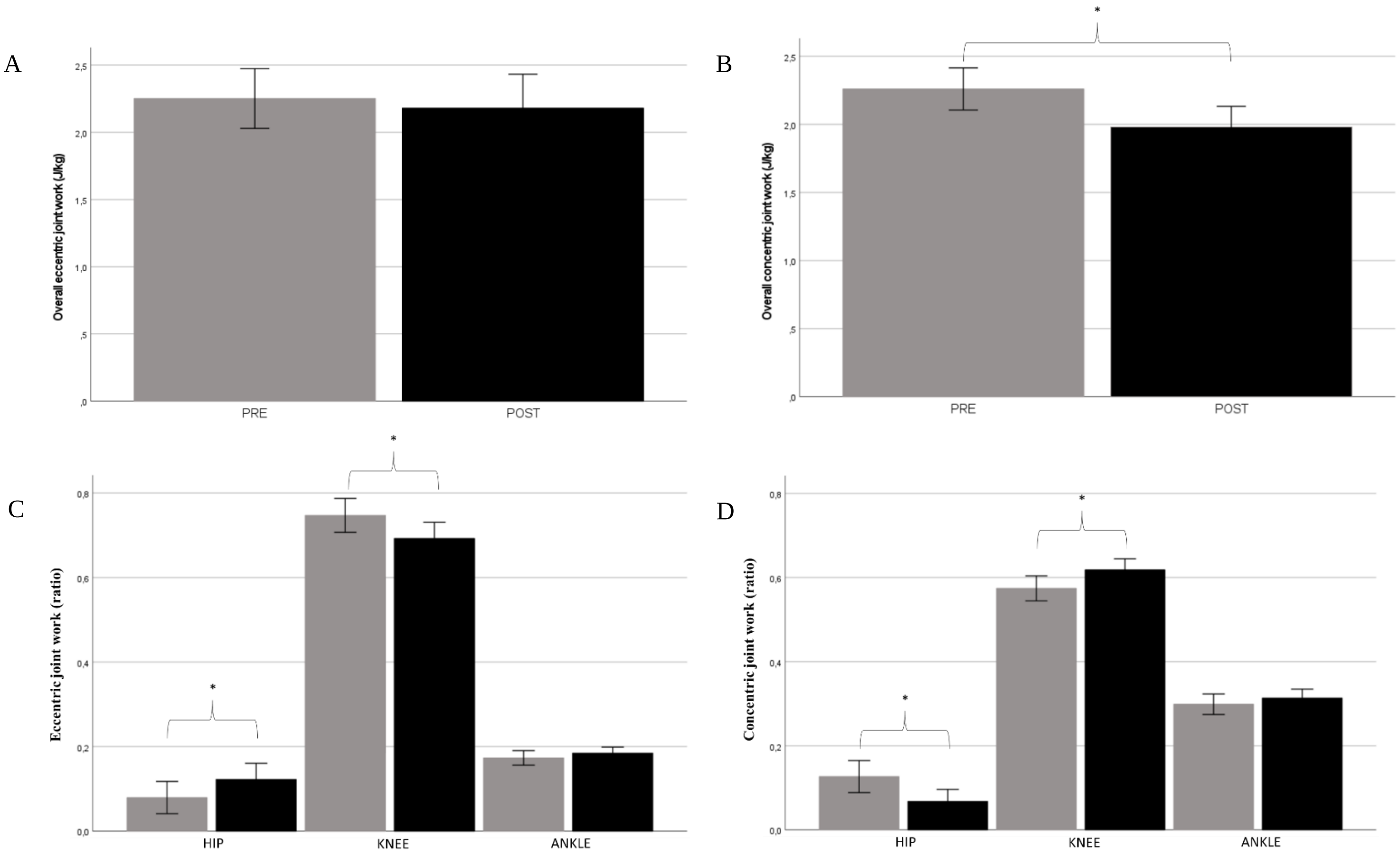

Figure 2: Joint work before and after the HIIP-5 (mean and 95% CI).

2A: overall eccentric joint work, 2B: overall concentric joint work, 2C: relative eccentric joint work, 2D: relative concentric joint work.

Pre-HIIP-5 = grey bar; post-HIIP-5 = black bar.

*Statistically significant difference between post-HIIP-5 compared to pre ($p<0.05$).

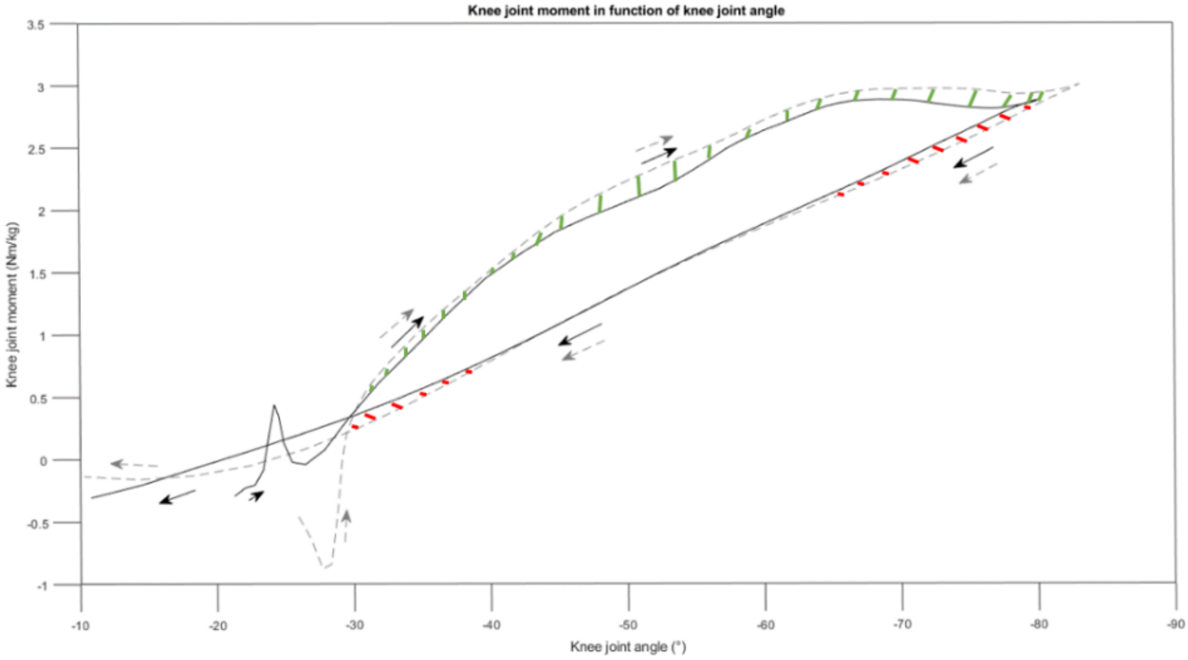

Figure 3: Moment-angle profiles of the knee joint.

Knee joint moment plotted against corresponding knee joint angles (pre-HIIP-5: grey, dashed line; post-HIIP-5: black, solid line). The surface underneath the curves represents the change in knee joint work. The green and red area between both curves indicate the decreased and increased work delivered by the knee joint post-HIIP-5 compared to pre, for the eccentric and concentric phases, respectively. The arrows indicate the direction of time.

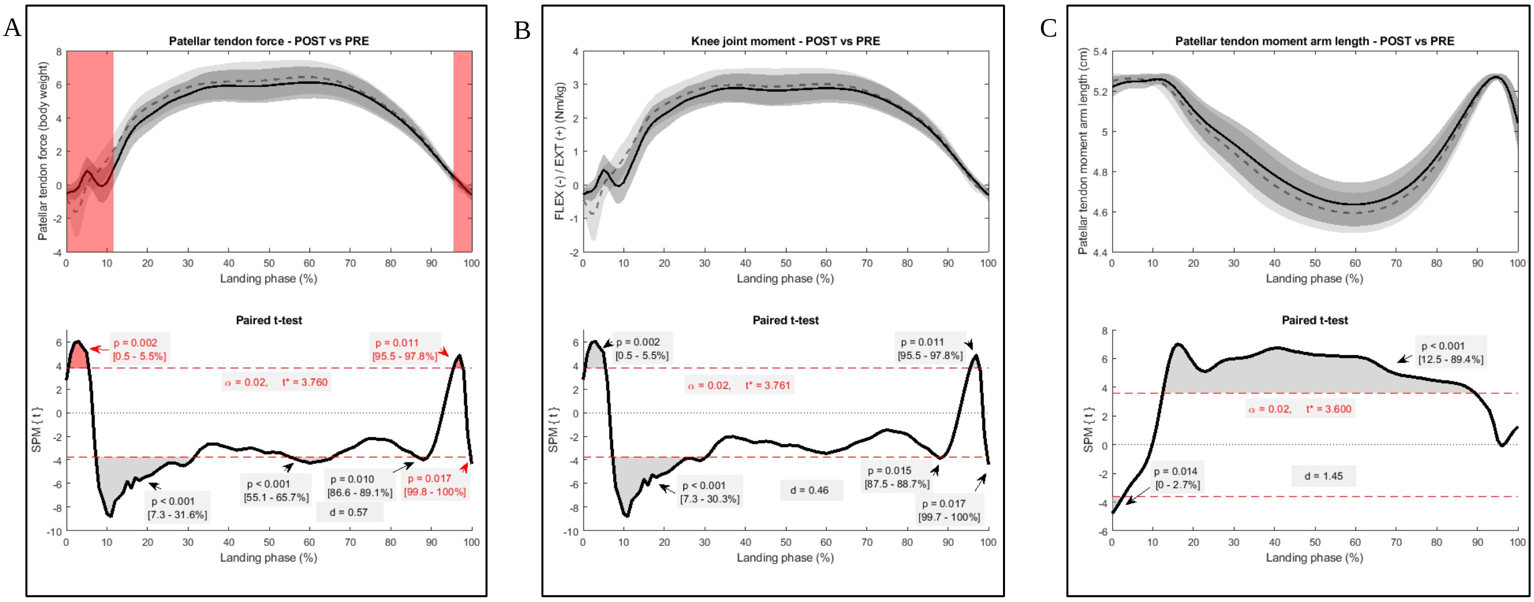

Figure 4: Patellar tendon loading before and after the HIIP-5.

4A: patellar tendon force, 4B: knee joint moment, 4C: patellar tendon moment arm length.

Kinematic and kinetic trajectories are presented as mean and standard deviation clouds in the upper row (pre-HIIP-5: grey, dashed line; post-HIIP-5: black, solid line) and SPM inference results in the lower row ($p<0.05$). Time zones for negative patellar tendon forces are highlighted in red and not interpreted as such.

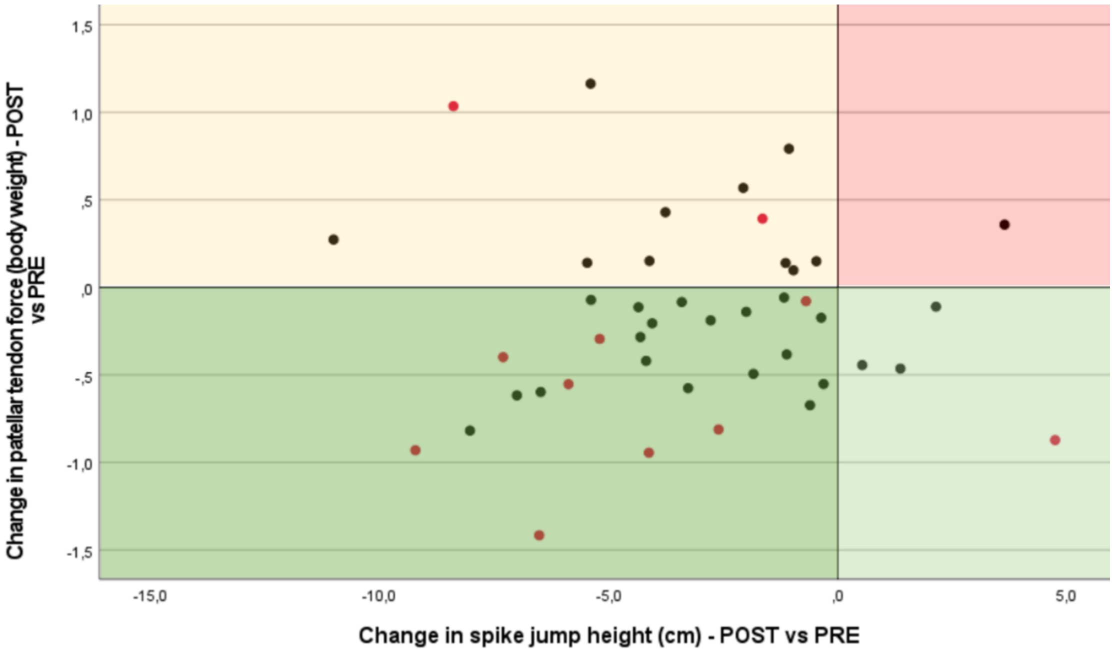

Figure 5: Hypothetical patellar tendinopathy injury risk profiles.

Players with low non-fatigued patellar tendon loading (<Q75, n=32) are presented with black dots, those with high non-fatigued patellar tendon loading with red dots (>Q75, n=11). After fatigue, hypothetical patellar tendinopathy injury risk increases according to the color of the quadrant (dark green → light green → yellow → red).

🟩 ↓ patellar tendon loading and ↓ jump height after fatigue (n=26)

🟩 ↓ patellar tendon loading and ↑ jump height after fatigue (n=4)

🟨 ↑ patellar tendon loading and ↓ jump height after fatigue (n=12)

🟥 ↑ patellar tendon loading and ↑ jump height after fatigue (n=1)

↓ Hypothetical patellar tendinopathy injury risk