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Research article

Adjusted Landing Technique Reduces the Load on the Achilles Tendon in Badminton Players

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Abstract
Achilles tendon (AT) rupture is common among recreational male badminton players. We hypothesize that a landing technique following forehand jump strokes with the landing foot in a neutral position often performed by recreational players and occasionally by elite players may expose the AT to higher loads than a scissor kick jump (SKJ) technique with the leg/foot externally rotated. The study aimed to investigate if recreational players could reduce the load in the AT when adopting the SKJ technique compared to their habitual landing technique with the foot in a neutral position and secondarily to compare the AT force between recreational players and elite players. Ten recreational male players performed simulated jump strokes in a biomechanical laboratory using both their original technique and the SKJ technique traditionally used by elite players. For comparison reasons ten elite players performed SKJs. Landing kinematics and AT forces were captured and calculated using 3D movement analysis. The landing leg was more externally rotated in the recreational players´ adjusted technique (78 ± 10 degrees, $p < 0.001$) compared to 22 ± 21 degrees in recreational players´ original technique. The peak AT force of the recreational players was significantly higher for the original technique compared to the adjusted technique (68 ± 19 N/kg vs. 50 ± 14 N/kg, $p = 0.005$). Additionally, the peak AT forces observed during the recreational players' original technique was higher, though not significantly, than those observed for elite players (55 ± 11 N/kg, $p = 0.017$). $\alpha = 0.016$ due to a Bonferroni correction. These findings indicate that recreational badminton players that normally land with the foot in a neutral position, may reduce their AT load by 25% when adopting the SKJ technique of elite players and land with the leg/foot in an externally rotated position.

Key words: Biomechanics, foot work, scissor kick jump.

Introduction

Achilles tendon (AT) ruptures are frequent in sports with high repetitive jump-landing and change of direction activities. The incidence is particularly high in badminton (Kaalund et al., 1989; Fahlström et al., 1998). In a national Danish AT rupture database registrations from 11 Hospitals in Denmark showed 21% (639/3059) AT ruptures to have occurred during badminton (Barfod et al., 2021). The incidence of AT ruptures in a Swedish population was reported to be 7 per 100.000 people/year (Fahlström et al., 1998). Male recreational players between 31 and 45 years were highly represented in the AT rupture population from Sweden with only one out of 31 players being an elite badminton player (Fahlström et al., 1998). Since the game inarguably is played at a much faster pace and involve more high-intensity actions at an elite level, one would expect that the elite players are exposed to higher loads, including the forces on the AT during jump-landing actions, yet injuries seem more prevalent among recreational players.

The AT ruptures can be devastating for the player and in worst case have career ending consequences (Kaalund et al., 1989). Furthermore, AT ruptures has significant socioeconomic influence for the individual and the society due to lost income and health costs (Truntzer et al., 2017; Costa et al., 2020). Despite badminton's high popularity in European and particularly Asian countries (Phomsoupha and Laffaye, 2015), our knowledge about the etiology and pathology behind AT ruptures in badminton is very limited.

Dynamic weight bearing jump-landing activities account for almost 80% of all AT ruptures during sports activities (Leppilahti and Orava, 1998; Maffulli, 1999; Gross and Nunley, 2016). Similarly a Danish study found that most AT ruptures in badminton occur during weight bearing single-leg landings on the rear part of the court close to the baseline (Kaalund et al., 1989). The AT load during traditional jump-landing activities is well documented in biomechanical literature (Kimura et al., 2012; Hung et al., 2020). However, the literature on badminton specific jump-landing activities has primarily focused on knee joint loading (Kimura et al., 2012; Shuhei et al., 2018; Zhao and Li, 2019; Hung et al., 2020). To the best of our knowledge, estimates of the AT loads experienced during badminton specific movements is limited to a single study on 26 English student club badminton players (Kuntze, 2008), where average peak AT forces of 43 N/kg for the trail limb and 37 N/kg for the leading limb were observed during lateral stepping (chassé steps). Thus, estimates of the AT loads badminton players experience during the most frequent injury situation, single-leg landings on the rear court, is yet to be explored. In vitro testing has shown ultimate tendon stress (i.e. tensile stress to failure) to be 100 MPa, whereas in vivo measurements of single-leg hopping have shown AT stresses up to 200 MPa (Maffulli, 1999). This indicates that stresses during sports situations may surpass the in-vitro measured AT failure thresholds, and it is therefore likely that the high impact landing after a maximal jump, as in the jump smash in badminton could result in a tendon stress jeopardizing the tendon.

Personal pre-study communications with coaches, elite and recreational players with a history of AT ruptures, indicate that AT ruptures often is associated with a neutral

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foot positioning during the landing phase, which may lead to an increased load on the AT.

According to experienced coaches, many recreational players often perform a backwards jump with minimal upper body rotation when returning the shuttlecock from the rear court. It may be influenced by the players` experience and the amount of technical supervision from coaches the recreational players have had. However, players at all levels may occasionally perform a backwards jump stroke with minimal upper body rotation. With minimal upper body rotation, the recreational players tend to land on their non-racket leg with the foot in a neutral position (toes pointing forwards in the direction of the net), and the ankle in a plantar flexed position, followed by a sudden dorsal flexion as part of the initial landing phase (Figure 1). In contrast, elite players frequently use the badminton specific scissor-kick jump (SKJ) technique with the landing leg externally rotated and the toes pointing towards the sideline when returning the shuttlecock from the rear court. The SKJ is a complex jump movement because the backwards jump is combined with a 180 degrees body-rotation along the players' longitudinal axis (Brahms, 2014) (Figure 1). The body-rotation creates the characteristic in-air crossing of the racket leg and non-racket leg (the non-racket leg is in front at take-off but brought to the back during the in-air body-rotation). The SKJ enables players to generate additional power in the stroke, as well as the ability to quickly push-off the ground upon landing and return to the middle of the court and the SKJ is therefore frequently used by elite players (Brahms, 2014; Zhang *et al.*, 2016). The frequency of SKJ per match varies depending on level and style of play, and has only been documented once in the current literature in a study based on observations from the African Championship, where an average of 38.3 SKJ was reported per match in men's single (Abdullahi and Coetzee, 2017). It is unknown how variations in landing technique, particularly leg/foot rotation, affects AT loading in jump strokes in badminton, and whether this may contribute to the higher incidence of AT ruptures among middle-aged male recreational players. We hypothesized that external foot position of the non-racket leg would have an influence on AT load.

The primary aim of this study was therefore to investigate if a subgroup of recreational players could reduce the load in the AT during forehand jump strokes landings, when adopting the SKJ technique compared to their habitual landing technique with the foot in a neutral position. The secondary aim was to compare the AT force between recreational players and elite players.

Figure 1. Recreational player original landing technique with the landing foot in neutral (A) vs. elite player landing technique with the landing leg externally rotated (B).

Methods

Participants

The study was designed as an explorative study with 20 subjects, 10 recreational and 10 elite male badminton players were recruited.

Based on in match-play evaluation of male badminton players from recreational clubs in the capital region of Denmark, 10 male recreational players were included. A former international elite player and elite coach identified the players. The 10 recreational players were recruited if the majority of their forehand jump strokes on the rear court were performed with an undesirable landing technique (the non-racket foot in a neutral position and dorsiflexion). These players were recruited for this study to demonstrate a possible injury risk situation since we found it unethical to ask players to do a non-habitual risk movement. The recreational players had played badminton between 1 and 10 years with limited educational instructions from coaches. To compare the landing technique and AT loading of recreational players with those of elite badminton players, 10 Danish national male badminton players were invited to participate in this study. Nine of the elite players were ranked top 100 in the world at the time of testing and one was a former top 10 player in the world.

None of the included players had a history of AT pain or injuries in the preceding 12 months to data collection, and their AT appeared normal on ultrasound images defined as a homogenous tendon without color doppler activity (Matthews *et al.*, 2020). The thickness of the AT as well as the distance from the skin to the superficial part of the AT was measured in prone with the ankle in neutral position in all three planes. These measures were recorded to estimate the AT moment arm. The ultrasound probe was placed in the longitudinal axis of the AT on the dorsal side and the distance was measured 1 cm proximal to the top of the calcaneus. All participants signed a written informed consent, and the study was approved by the local ethics committee (VD-2019-40).

Experimental protocol

After a 15-minute standardized warm-up routine, the recreational players completed a series of simulated forehand jump strokes. The recreational players were asked to perform two simulated forehand jump stroke variations. First, they performed habitual original landing technique (recreational original landing, ROL), i.e., a backwards jump landing on their non-racket leg (Figure 1A). The players were asked to land with their non-racket foot on the force plate. Due to the limited floor-to-ceiling height in the biomechanical laboratory, participants were instructed to perform the jump strokes without a racket. To facilitate a natural upper-body stroke movement, participants were instructed to hit a target suspended from the ceiling above the force platform with their normal racket-hand.

After a demonstration of the SKJ by the test instructor (first author), who is also an experienced elite badminton coach, the recreational players completed an individual number of familiarisation trials. The recreational players were instructed to perform forehand jump strokes adopting the SKJ technique (recreational adjusted landing, RAL) with special focus on in-air body-rotation and landing with the non-racket leg externally rotated and the foot in an external rotated position on the force plate (Figure 1B). Only RAL jumps where the SKJ technique were approved by the investigators were included in the data set.

After a 15 min standardized warm up routine the elite players were instructed to perform a series of SKJ (ELITE), as they normally would.

Participants in both the recreational and elite group completed an individual number of submaximal jumps, until five successful trials were recorded for each condition landing on their non-racket leg with the foot correctly inside the force platform. Rest between jumps were in average 45 seconds to avoid fatigue. In order to standardize loading impact between jumps (ROL and RAL) and groups (recreational and elite players), the participant initiated the jump from a fixed distance in front of the force plate corresponding to 50 % of the leg length (measured length from the medial malleolus to the anterior superior iliac spine). Moreover, after each jump participants were instructed to accelerate forward immediately upon landing and reach a target placed 3 meter in front of the force platform.

Measurements and data analysis

Three-dimensional lower limb kinematics were recorded with an eight T40 Vicon camera motion capture system (Vicon Motion Systems Ltd, Oxford, UK) at 200 Hz, and synchronized with three-dimensional ground reaction forces (GRF) measured with an AMTI force platform (OR-6-7, AMTI, Massachusetts, USA) sampling at 1000 Hz. Segment kinematics were captured with 24 retroreflective markers attached to the pelvis, lower limbs and the subjects´ shoes using the modified Helen-Hayes marker set outlined in Bencke et al. (2013) (2013). Kinematic marker trajectory data were filtered with a Woltring cubic spline filter (Woltring, 1986), whereas GRF data were filtered using a zero-lag fourth order low-pass Butterworth filter with a cut-off frequency at 50 Hz using inherent Vicon Plug-in-Gait software (Nexus 2.9, Vicon Motion Systems Ltd, Oxford, UK). External foot position, ankle joint kinematics and external ankle joint moments were calculated for the non-racket leg during the landing phase, using the aforementioned Vicon software. The landing phase on the force platform was determined from the vertical GRF, where foot strike and take off were defined using a 10 N threshold. Additionally, net positive and negative joint work were calculated for the hip, knee and ankle joints during the landing phase by integrating the positive and negative parts of the instantaneous joint power curves with respect to time. Furthermore, peak vertical (vGRF), sagittal (sGRF) and transverse (tGRF) ground reaction forces were calculated for the landing phase, where sGRF was defined as the force in the direction of the net (forward) and tGRF was defined as the force in direction of the sidelines.

Achilles tendon force (AT Force) was calculated from the plantar flexor ankle moment (M_{Ankle}) and estimated AT moment arm (AT_{MA}) (Eq. 1) (Kernozek *et al.*, 2017). Individual AT_{MA} was calculated from trigonometry using foot/ankle kinematics and static ultrasound measurements of the participants AT and under the assumption that the AT_{MA} was perpendicular to the long axis of tibia throughout the entire landing phase.

$$AT\ Force = \frac{M_{Ankle}}{AT_{MA}} \qquad \text{(Eq. 1)}$$

Peak jump height was defined as the peak vertical height of the two posterior superior iliac spine (PSIS) markers during the jumps, subtracted, by the average vertical position recorded during a static standing trial. Moreover, average forward velocity ($V_{Forward}$) was calculated from the last contact on the force platform to the first timeframe where both PSIS markers crossed an imaginary line 1.5 meter in front of the force platform.

Statistical analysis

Since the study was designed as an explorative study, and no previous comparable data on this topic has been published, no power analysis was performed. The average of five trials of each jump type was calculated for the participants and used for the statistical analysis. All kinetic data (joint moments, joint work and AT force) were normalised to body mass. Paired t-tests were used to evaluate differences between the two jump conditions for the recreational group (ROL vs RAL), with an $\alpha = 0.05$. Whereas an independent t-test with Bonferroni correction ($\alpha = 0.016$) was used to evaluate differences between the recreational groups' two jumps and the elite group's SKJ (ELITE). Additionally, Cohens´ d (effect size) was calculated for all parameters. All statistical analyses were performed using SPSS statistical software (version 25, SPSS Inc. Chicago, IL, USA).

Results

There were no significant differences in age, height, body mass or AT characteristics (AT thickness and skin thickness) between the recreational and elite players (Table 1).

ROL vs RAL

The analysis revealed that the recreational players significantly altered their landing mechanics during the RAL compared to ROL, without compromising performance parameters such as jump height and forward velocity (Table 2). The recreational players landed with leg/foot in a significantly more external rotated position (78 ± 10 degrees) compared to the ROL (22 ± 21 degrees, p < 0.001, d=2.34). In contrast, there was no significant difference in peak dorsiflexion angle between ROL and RAL.

The change from ROL to RAL was associated with a significant reduction in the recreational players peak absolute AT force (5278 ± 1227 N vs 3960 ± 1181 N, p = 0.003, d = 1.30) and AT force relative to body weight (67.7 ± 18.9 N/kg vs 50 ± 14 N/kg, p = 0.005, d = 1.17). There were no significant differences in peak M_{Ankle} or AT_{MA} between the ROL and RAL jumps. The adjusted landing technique (RAL) was associated with significantly higher peak landing GRFs in all planes compared to the ROL (Table 2).

Finally, the adjusted landing technique significantly altered the landing joint work distribution of the test leg (Figure 2). More specifically, the RAL was associated with significantly lower negative and positive joint ankle work, compared to the ROL. Whereas significantly greater negative and positive hip joint work was observed for the RAL compared to the ROL.

Recreational vs Elite players

The elite players jumped significantly higher than the recreational players and accelerated faster forward than the recreational players (Table 2). Similarly, the elite players had greater vGRF, tGRF and sGRF compared to the ROL, whereas the elite players only experienced greater vGRF and tGRF compared to the RAL (Table 2).

The independent t-tests revealed that the elite players landed with the non-racket leg significantly more externally rotated (82 ± 4 degrees, p < 0.001, d = 3.96) compared to the recreational players in the ROL (Figure 3A). When the recreational players applied the adjusted landings, they were able to mimic the elite players SKJ technique and reached external rotations of the foot similar to those of elite players (Table 2). Moreover, similar peak dorsiflexion angles, peak M_{Ankle} and AT_{MA} were observed between the elite players and the recreational players (both ROL and RAL conditions) (Table 2).

Table 1. Anthropometric profiles and statistical comparison between the recreational and elite group. Variables are expressed as mean ± SD

Variable	Recreational	Elite	t	*P*	95% CI Diff
Age (years)	28.1 ± 6.3	28.2 ± 7.6	-0.03	0.98	-6.8 to 6.7
Height (m)	1.83 ± 0.06	1.81 ± 0.05	0.90	0.38	-2.9 to 7.3
Weight (kg)	79.7 ± 10.5	72.4 ± 6.6	1.84	0.09	-1.0 to 15.5
AT thickness (mm)	3.9 ± 0.4	4.2 ± 0.9	-0.86	0.40	-0.9 to 0.4
Skin thickness (mm)	2.3 ± 0.5	2.1 ± 0.8	0.49	0.63	-0.5 to 0.8

AT: Achilles tendon; t: test statistic; *P*: probability value; 95% CI Diff: 95% confidence interval for the difference.

Table 2. Means ± SD and statistical comparison between ROL, RAL and ELITE.

Variable	ROL	RAL	ROL vs. RAL			ELITE	vs. ROL			vs. RAL		
			t	*P*	*d*		*t*	*P*	*d*	*t*	*P*	*d*
Jump Height (cm)	14.3 ± 8.2	19.4 ± 7.8	-2.22	0.053	-0.70	30.6 ± 9.8	**-4.03**	**0.001***	**-1.80**	**-2.83**	**0.011***	**-1.27**
Contact Time (ms)	460 ± 130	470 ± 120	-0.45	0.665	-0.14	368 ± 48	2.07	0.062	0.93	2.35	0.038	1.05
Average Forward Vel (m/s)	3.9 ± 0.7	4.0 ± 0.9	-0.24	0.816	-0.08	4.9 ± 0.4	**-3.35**	**0.004***	**-1.75**	-2.53	0.026	-1.29
Peak vGRF (N/kg)	19.8 ± 3.4	26.9 ± 4.6	**-6.13**	**<0.001***	**-1.94**	34.2 ± 6.6	**-6.12**	**<0.001***	**-2.74**	**-2.86**	**0.010***	**-1.28**
Peak tGRF (N/kg)	10.9 ± 2.6	13.4 ± 2.9	**-4.29**	**0.002***	**-1.35**	17.9 ± 2.3	**-6.41**	**<0.001***	**-2.87**	**-3.84**	**0.001***	**-1.72**
Peak hGRF (N/kg)	1.5 ± 0.8	6.8 ± 2.3	**-8.00**	**<0.001***	**-2.53**	8.1 ± 3.6	**-5.53**	**<0.001***	**-2.47**	-0.94	0.362	-0.42
Ext. Foot Pos (°)	-22 ± 21	-78 ± 10	**7.39**	**<0.001***	**2.34**	-82 ± 4	**8.86**	**<0.001***	**3.96**	1.25	0.236	0.56
Ankle Angle at IC (°)	-16 ± 13	-22 ± 9	2.16	0.059	0.68	-17 ± 9	0.31	0.760	0.14	-1.11	0.281	-0.50
Peak Ankle Angle (°)	38 ± 9	36 ± 7	1.38	0.200	0.44	34 ± 7	1.16	0.261	0.52	0.45	0.659	0.20
Peak M_{Ankle} (Nm/kg)	3.1 ± 0.5	2.5 ± 0.4	2.88	0.018	0.91	2.9 ± 0.3	1.22	0.237	0.55	-2.24	0.038	-1.00
Peak AT_{MA} (mm)	47.9 ± 8.9	51.5 ± 9.0	-1.81	0.103	-0.57	52.4 ± 8.5	-1.16	0.262	-0.52	-0.24	0.813	-0.11
Peak AT Force (N)	5278 ± 1227	3960 ± 1181	**4.10**	**0.003***	**1.30**	4007 ± 899	2.64	0.017	1.18	-0.10	0.921	-0.05
Peak AT Force (N/kg)	67.7 ± 18.9	50.1 ± 14.2	**2.38**	**0.005***	**1.17**	55.3 ± 10.7	1.82	0.085	0.81	-0.92	0.368	-0.41

* indicate significant different at an alpha level of 0.016 (Bonferroni correction). ROL: recreational original landing; RAL: recreational adjusted landing; ELITE: elite player scissor kick jump; t: test statistic; P: probability value; d: Cohen's d effect size; $V_{Forward}$: average forward velocity; vGRF: vertical ground reaction force; tGRF: transverse ground reaction force; hGRF: horizontal ground reaction force; Ext. Foot Pos: external foot position; A negative external foot position corresponds to an external rotation; A positive ankle angle is corresponding to a dorsi flexion angle; M_{Ankle}: Sagittal ankle moment; AT_{MA}: Achilles tendon moment arm; AT: Achilles tendon; IC: initial contact.

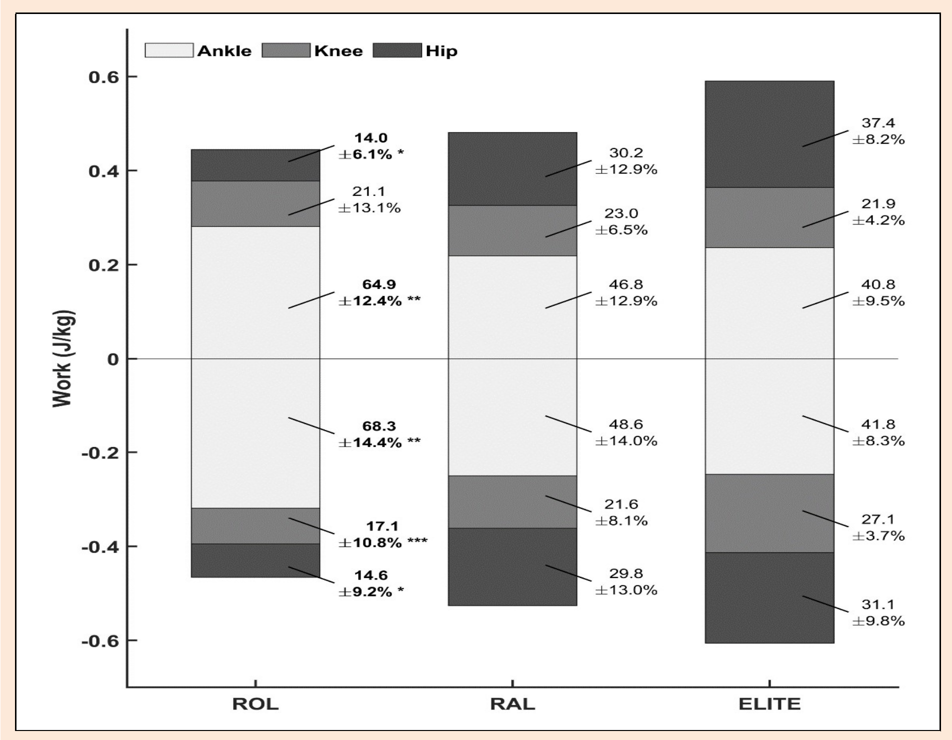

Figure 2. Positive and negative mean joint work distribution and SD for the ROL, RAL and ELITE. * Indicates that the hip joint work of the ROL is significantly lower ($P < 0.016$) than the RAL and ELITE. ** Indicates that the ankle joint work of the ROL is significantly higher than the RAL. *** Indicates that the negative knee joint work of the ROL is significantly lower than the ELITE.

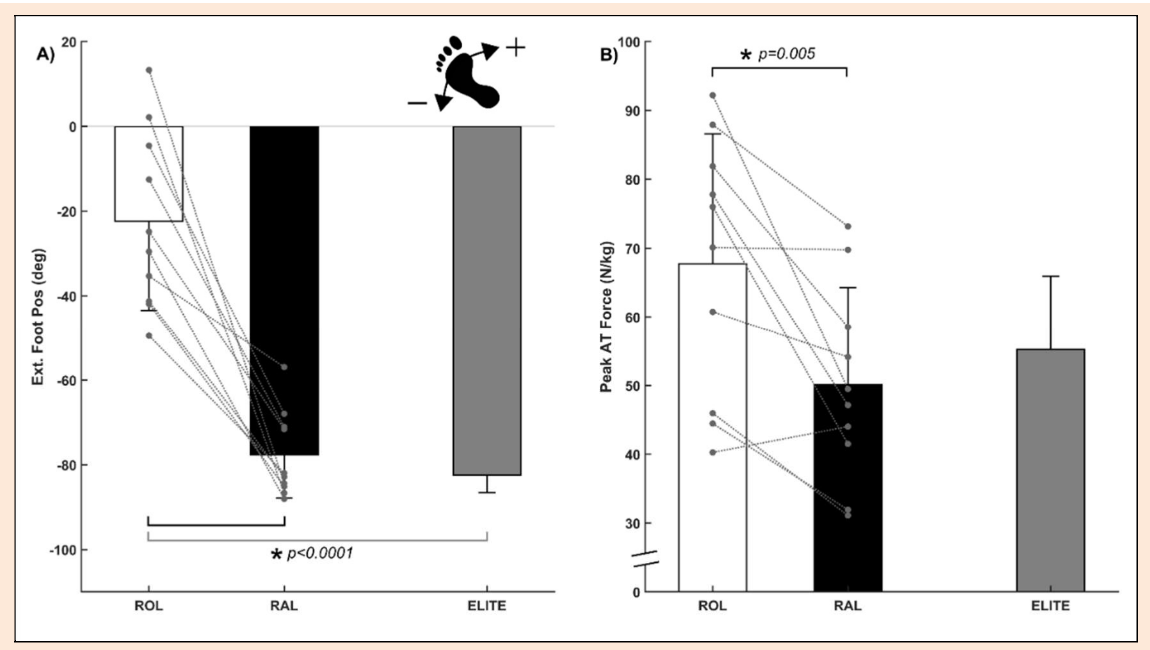

Figure 3. Group mean ± SD and statistical comparisons for A) external foot position (Ext. Foot Pos) and B) peak Achilles tendon force (AT Force) for the ROL, RAL and ELITE. The grey dots indicate the individual mean data for the recreational players original landing technique (ROL) and adjusted landing technique (RAL). * Indicates significant difference between landings ($P < 0.016$, with Bonferroni correction).

No difference was found in AT forces between the elite players and the ROL and RAL (Table 2.). Though the elite players experienced lower, but not significantly, absolute peak AT forces (4007 ± 899 N, p = 0.017, d = 1.18) and AT forces relative to body weight (55.3 ± 10.7 N/kg, p = 0.085, d = 0.81) than the recreational players experienced with their ROL (Figure 3B). The highest measured peak AT Force for a trial among all players was 100 N/kg and 8632 N in a ROL.

Finally, the elite players generally absorbed and generated a higher amount of total joint works across the hip, knee and ankle joints during the landing phase compared to the recreational players (Figure 2). The elite players exhibited significantly greater positive hip joint work and greater negative hip and knee joint work than the recreational players during their ROL. Whereas similar joint work distribution was observed between elite players and the recreational players when they adopted the elite players' technique (RAL).

Discussion

In the present study, recreational badminton players original landing technique following a simulated forehand jump stroke on the rear court was compared to an adjusted technique where they mimicked the SKJ technique of elite players. The study revealed a 25% reduction in estimated AT forces in the non-racket leg when the group of recreational players adopted elite players SKJ technique. Moreover, the results demonstrated that the recreational players, following a quick instruction, were able to mimic the elite players SKJ technique, and land with the foot in a more externally rotated position and reduce the AT forces. Unapproved RAL-trials were predominantly due to the player failed to land with the foot inside the force plate and only a few times due to a failure of adapting the SKJ technique. Though the elite players jumped higher and generally were exposed to higher GRFs, recreational players still experienced higher AT forces, though not significant ($p = 0.017$), with their original landing technique following a forehand jump stroke.

ROL vs. RAL

Inexperienced badminton players generally rotate the upper body less than experienced players during overhead jump strokes (Zhang et al., 2016). This is probably because it is easier to control the timing of the jump stroke with less body rotation. As a result, players may land with their non-racket leg in a less externally rotated position as observed in this study. However, the situation of jumping backwards and landing with the purpose of a subsequent fast acceleration forward towards the net would require that the center of mass is placed more anteriorly. Thus, landing with a more anteriorly directed foot position, as in the original landings of the recreational players, will potentially place the center-of-pressure towards the toes and as a consequence develop a larger external ankle moment arm. This would in turn potentially contribute to a larger internal ankle joint moment (M_{Ankle}). Since the AT_{MA} did not change between the ROL and RAL in this study, the increase in joint moment may be caused by an increase in AT force exerted by the triceps surae muscle during the ROL.

Interestingly, the change in landing technique from ROL to RAL did not affect the performance outcomes in the recreational group. Neither jump height, contact time nor forward velocity was changed, despite a reduced M_{Ankle}. However, the GRF data showed a total increase of produced peak force summated across the ankle, knee and hip joint. Examining the work contribution of the different joints it appeared that the diminished contribution from the ankle joint was compensated by an increase in both concentric and eccentric hip joint work (Figure 2). This indicates that the change in landing technique appear to be an easy and very compelling way of reducing AT force with no negative consequences on performance. However, the change in joint load distribution may increase the risk of injuries in other body parts and an implementations of new technique must be done with care to avoid overload injuries.

Recreational players vs. elite players

The elite players performed significantly better than the recreational players in jump height and forward velocity after the landing, and a non-significant tendency toward a shorter contact time. As expected, the peak GRF was also significantly larger than both conditions of the recreational players. No difference was observed in the dorsi- or plantarflexion angles, but the elite players displayed greater external rotation of the foot during their SKJ. As shown in Figure 2, the increased performance of the elite players is obtained by a significantly higher work production of especially the hip joint, while the work contribution from the ankle joint is not different from the recreational players. Given the larger physical capacities of the elite players, it may be speculated that if an elite player landed with the foot in a less external rotated position, like in the ROL condition, the increase in AT force would be even higher and thus the risk of a AT injury would increase.

Implications for AT injury risk

As well as AT ruptures AT pain are also frequent among badminton players (Boesen et al., 2006; 2011). AT ruptures have other implications on life than return to sport and daily living. In the study by Fahlström et al. (1998), the nonsurgical treated players had a sick leave of 75 days compared to 49 days in the surgical treated group. There is no recent publication on return to badminton after AT ruptures but in our department we allow tournament players to return to competition after 6 months. In the study by Kaalund et al. (1989), 46 % resumed badminton in 6 months and 82 % in 12 months. Twenty-five percent did not regain their level of badminton.

The AT injury risk in badminton reported in the literature is multifactorial but the ATs capacity of absorbing load and the total load in the AT may be key elements (Kaalund et al., 1989; Fahlström et al., 1998). As expected, the peak AT forces experienced across the high-impact jump movements in our present study (up to 100.4 N/kg and 8632 N), were larger than those observed for chassé steps in the study by Kuntze (2008). Yet, elite badminton players may experience even higher AT forces during badminton specific landings. A study by Hung et al. (2020) reported higher peak plantar flexor moments during lateral backhand jump smash landings (3.3 ± 0.1 Nm/kg) in elite Taiwanese male badminton players, suggesting AT forces even higher than reported in the present study, given the same moment arms and body weight (Hung et al., 2020). In contrast to the present study, the players in the study by Hung et al. (2020) was not limited in jump performance (ceiling height) which may explain the higher plantar flexor moments.

The AT forces estimated for both the recreational and elite players in the present study is similar to those estimated in healthy male subjects during single-leg jump landing tasks over a barrier (AT forces between 4633 and 6286 N) and in barefoot drop landing (between 3565 and

3713N) (Whitting et al., 2011; 2012; Gheidi et al., 2018; Gheidi and Kernozek, 2019). The peak AT forces found in the present study and in the aforementioned studies are generally higher than the peak AT forces found from in-vivo measurements in hopping (3500-4000N) (Fukashiro et al., 1995; Lichtwark and Wilson, 2005). To understand the potential consequences of the AT forces estimated in the present study it could be noted that AT failure ranges between 4635-5579 N was previously reported in cadaveric studies (Wren et al., 2001; Rees et al., 2008) and the highest measured AT force in our study was 8632 N. Although cadaveric studies may underestimate the failure limit in healthy tissue, these values still indicate that the eccentric landing characteristics observed in badminton during the initial contact phase directly followed by a concentric phase may impose greater loading of the AT, making it a potential high-risk AT injury movement in badminton (Fukashiro et al., 1995; Whitting et al., 2011; 2012; Gheidi and Kernozek, 2019).

The present study shows that this group of recreational players tend to land with their non-racket leg less externally rotated, thus imposing greater loads on the AT following a forehand jump stroke which may expose them at greater risk of sustaining an AT rupture. Nevertheless, elite players also sustain AT injuries despite habitual optimal technique. It is not clear, why these injuries happen in elite players but non-optimal variations in technical execution of the movement in risk situations may among other things offer an explanation. Biomechanical studies on the knee joint loading during side cutting in ball sports, show significantly increased and unfavorable knee joint loading during unanticipated side cutting compared to anticipated, illustrating that the pre-planned dynamic control may not always control the joints optimally in situations where fast decision making is required (Fukashiro et al., 1995). Likewise, in badminton non-predictable variations in the fast game situation may challenge the perception and slightly alter the landing technique, e.g., landing with the leg in a less externally rotated foot position, resulting in higher load on the AT as shown in the present study. Similarly, fatigue may alter the players' landing technique and increase the tendon load.

Pre-existing conditions like tendinopathy may also lower the threshold of rupture due to changes in stiffness and strength of the tendon fibers (Yasui et al., 2017; Dakin et al., 2018). As in running, discomfort related to Achilles tendinopathy may alter badminton players movement pattern and increase the load on the AT, yet the association between landing technique and Achilles tendinopathy among badminton players is still unknown (Sancho et al., 2019). Thus, it is possible that the higher AT forces observed for recreational players that repeatably employ the undesirable landing technique with the foot in a less externally rotated position, over time may increase the risk of Achilles tendinopathies and hence increase the risk of rupture, however, this also needs to be confirmed in future studies.

Limitations

A potential limitation of the study is that the small sample size could lead to underpowered data. Due to the explorative nature of the study a priori power analyses were not possible, however a post-hoc power analysis was performed for the primary outcome, i.e. the change in load of the AT between the ROL and RAL jumps. With the reported Cohen's effect size of d=1.3 the power of the study was 95%. Using a generally accepted power level of 80% a change in load equal to an effect size of d=1.0 would be required to show significance at an α=0.05. This emphasizes that the potential of load reduction, as a result of the change in technique, is large however individual differences in e.g. jump height and landing impulse between the two landing techniques would also influence the load of the AT.

Another limitation with this study is that the players performed the jump variations without a racket and shuttlecock, due to the limited laboratory floor-to-ceiling height, however the movements were supervised and approved by an experienced badminton coach as resembling natural badminton movements. Further, with our study design and the joint mechanics presented is that the ground reaction forces only were measured for the non-racket leg, though players had double support in the last part of the SKJ landing. We did however focus on joint kinetics of the non-racket leg in this study because it indisputably is exposed to the highest loads during the SKJ landings and generally more exposed to severe injuries (e.g. knee injuries) than the racket leg in badminton (Kimura et al., 2010). AT forces were estimated from net joint moments obtained by inverse dynamics, though we acknowledge that this method does not account for co-contraction and biarticular muscle forces. Nevertheless, Kernozek et al. (2017) found similar peak AT force from inverse dynamics and inverse dynamic based static optimization methods for submaximal running. Therefore, the less time-consuming inverse dynamic methods was implemented in this study. Finally, the AT images obtained from ultrasound, to calculate the AT_{MA}, were restricted to the longitudinal view, which did not enable us to calculate the players´ AT cross-sectional area, thus the AT stress and strain were not calculated.

Conclusion

The present results show that a group of recreational badminton players with an undesirable landing technique can reduce their landing AT load 25 % when adapting the SKJ technique, traditionally employed by elite players, without compromising performance parameters such as jump height. These findings emphasize the importance of landing technique, particularly external leg/foot position, during badminton specific landings to reduce AT load since it may lower the risk of AT ruptures and tendinopathy in both recreational and elite players. The simplicity of focusing on external foot position in jump stroke landings to reduce AT loads imply that effective implementation is possible. The findings suggest that badminton coaches should focus on upper-body rotation during forehand jump strokes to facilitate the external leg/foot position in the subsequent landing, to lower AT forces and potentially the risk of sustaining an AT injury. Nevertheless, additional studies are required to confirm causative relationship between landing techniques and AT injury or pathology, including studies on landing profiles of recreational and elite players with and without AT injuries or pathologies in more game-like situations with unanticipated actions.

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Key points

- The Achilles tendon load is influenced by the rotation of the lower leg when badminton players perform scissor kick jump on the rear court in badminton.
- The subgroup of recreational players in the present study reduced their AT landing forces significantly when adapting the scissor-kick jump technique, traditionally employed by elite players, without compromising performance parameters such as jump height.
- The AT landing forces of recreational badminton players who perform forehand jump strokes with minimum upper-body rotation, may exceed those elite players experience during scissor-kick jump landings.
- These findings suggest that badminton coaches should focus on upper-body rotation during forehand jump strokes to facilitate the external leg/foot position in the subsequent landing, to lower AT forces and potentially the risk of sustaining an AT injury.

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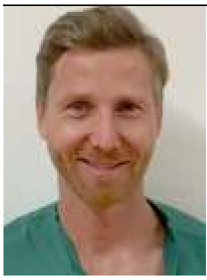

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