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Relation Between Ankle Joint Dynamics and Patellar Tendinopathy in Elite Volleyball Players

*†David P. Richards, MD, †Stanley V. Ajemian, MSc, ‡J. Preston Wiley, MD, MPE, *Jacques A. Brunet, MD, MSc, and †‡Ronald F. Zernicke, PhD

**Division of Orthopaedic Surgery, Department of Surgery, The University of Ottawa, Ottawa, Ontario; †McCaig Center for Joint Injury and Arthritis Research, Faculty of Medicine; and ‡Sport Medicine Center, Faculty of Kinesiology, The University of Calgary, Calgary, Alberta, Canada*

Objective: Ankle joint complex dynamics developed during volleyball spike jumps take-offs and landings were quantified to assess potential relations between these joint dynamics and patellar tendinopathy.

Design: Three-dimensional kinematic data provided information about movements of the lower limbs, while the kinetic data permitted analysis of ground reaction forces as players took-off and landed from full-speed spike jumps.

Setting: Simulated volleyball court with net in a biomechanics research laboratory.

Participants: 10 members of the Canadian Men's National Volleyball Team. From history and physical examination, 3 of the 10 players had patellar tendon pain associated with activity and were diagnosed with patellar tendinopathy at the time of the study. Investigators were blinded about the injury status of the players.

Interventions: None.

Main Outcome Measures: Three-dimensional kinematics and joint moments of the ankle, knee, and hip joints.

Results: Our analysis revealed that maximal external tibial rotation occurred at or near maximal dorsiflexion while maximal internal tibial rotation coincided with maximal plantarflexion. The plantarflexion moment was 3 to 10 times greater than all the other moments measured, with the maximal plantarflexor moment being calculated at 0.4 BWm (360 Nm). In blinded logistic regression analyses, we found one of the dynamics variables (inversion moment during the landing of the spike jump) was a significant predictor of patellar tendinopathy.

Conclusions: Coupling the results of the current analysis of ankle joint complex dynamics with previously reported results of knee joint dynamics related to patellar tendinopathy suggests that a cluster of variables linked to patellar tendinopathy includes: high ankle inversion–eversion moments, high external tibial rotation and plantarflexion moments, large vertical ground reaction forces, and high rate of knee extensor moment development.

Key Words: Biomechanics—Patellar tendinopathy—Ankle—Dynamical analysis.

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INTRODUCTION

A majority of sport-related injuries result from overuse of the musculoskeletal system.[1,2] Among overuse injuries, the quadriceps mechanism (e.g., patellar tendon) can be traumatized from the repetitive loads placed on the knee during activities such as jumping.[3–14] Patellar tendinopathy is commonly seen in volleyball due to the repetitive jumping that occurs during practice and play. In training, the players are frequently involved in plyometric exercises such as drop jumps. This involves a maximal jump after landing from jumps of various heights,[5,15] and at elite levels of competition, the intense training and the numerous scrimmages and games cause repeated stress to the player's extensor apparatus. As a result the patellar tendon is commonly injured.[3–9,13,14] Ferretti[5] found patellar tendinopathy to be the most frequent injury in elite volleyball players, with an incidence of 28–40%. Numerous studies have examined knee joint dynamics during jumping and its association with patellar tendinopathy,[10–13,15–28] but gaps exist in our understanding of the ankle joint complex and its potential role in the lower extremity's dynamic linkage related to patellar tendinopathy during jumping. Thus, here we extended our earlier study[23] in which we examined knee joint dynamics to find predictors of patellar tendinopathy. The purpose of the current analysis was to quantify the ankle joint complex (AJC) dynamics during volleyball jumps and to determine the potential relations of volleyball jump AJC dynamics to patellar tendinopathy.

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Address correspondence to Ronald F. Zernicke, PhD, Faculty of Kinesiology, University of Calgary, 2500 University Drive NW, Calgary, AB, Canada, T2N 1N4. E-mail: zernicke@ucalgary.ca

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METHODS AND MATERIALS

Subjects

Eleven members of the Canadian Men's National Volleyball Team participated in this study. During the study period, the players gave their informed consent for a medical interview and a physical examination that took place at the University of Calgary Sport Medicine Centre. The clinical criterion for diagnosing patellar tendinopathy was anterior knee pain during activity and a complaint of tenderness to palpation at the inferior pole of the patella.[3]

Kinematic and Kinetic Data Acquisition

The three-dimensional (3D) kinematic data provided information about movements of the lower limbs, while the kinetic data permitted analysis of ground reaction forces. Kinematic and force data were combined in a rigid-body model that permitted an analysis of the lower extremity inverse dynamics.[23] High-speed video digitizing (200 frames/s) generated the limb coordinate data. Four video cameras were placed in a semicircle around the testing site. The cameras recorded the 3D coordinates of the segments of the lower extremity by digitizing (VP 320; Motion Analysis Corporation, Santa Rosa, CA, U.S.A.) the images of 1.5 cm reflective markers taped to the skin (or shoe) over anatomic landmarks on the limb closest to the cameras. Three markers for each segment were used to determine the 3D position and movement of the specific segment. The markers were placed in the following positions: greater trochanter of the femur, anterior thigh, lateral femoral condyle, tibial tuberosity, midfibula, distal fibula, calcaneus (below the lateral maleolus), superior navicular, and lateral border of the fifth metatarsophalangeal joint. The foot markers were placed on the athlete's shoes after palpating and identifying the appropriate anatomic location. Placing the markers on these anatomic sites allowed for a 3D joint coordinate system to be created for the hip, knee, and ankle.[29]

Prior to video data collection of the jumps, each player completed a standing trial. In the "standing trial," a video image of the subject in anatomic position was recorded, and the coordinate data from this reference trial were transformed to determine the position of the markers relative to the estimated joint centers. This information allowed a segment coordinate system relative to the joint centers to be established. A segment coordinate system allowed the comparison of one segment's position relative to another and their relative changes in position with respect to time.[29]

Kinetic data were acquired with the use of a force plate (90 × 60 cm) (Kistler Instrument Corp., Amherst, NY, U.S.A.) that was embedded in the laboratory floor. The force plate allowed the measurement of the 3D forces (x, y, z) during the volleyball spike jumps. The force data were collected at 1,000 Hz and relayed to a computer workstation (Sparc II; Sun Microsystems, Inc., Mountainview, CA, U.S.A.) where the data were synchronized to the kinematic data and analyzed.

Experimental Design

Since our intent was to provide the players with game-like and practice-like situations, the Human Performance Laboratory was set up to simulate a volleyball court. The net was integral to the experiment and provided the flexibility to move the standard depending on the type of jump being tested; the net conformed to official volleyball dimensions. The net was set at regulation height (2.43 m) and spanned 4.5 m. Spiked balls were snagged in large floor-to-ceiling nets, hung approximately 5 m beyond the volleyball net.

Before participating in the study, the subjects read and signed an approved consent form (University of Calgary). The players then spent 10–30 minutes stretching and riding a bicycle ergometer to ensure that they were "warmed-up" before initiating their jumps. When the players felt sufficiently prepared, the reflective markers were placed on their legs, several practice trials were taken by each player to become accustomed to the experimental setup, and the data acquisition began.

The experiment was designed to gather data from the take-offs and the landings of spike jumps. Three trials were collected for both the spike take-off and landing. In all jump take-offs and landings, only one foot contacted the force platform. Because of the players' advanced skill level, their consistent performance, and the highly accurate ball tosses, only a few practice trials were needed before they reliably achieved the one-foot take-off or landing from the force platform.

The spike jump take-off was measured as the players attacked from the strong side (e.g., they approached from the left side of the court and spiked with their right hand). To ensure a realistic and reliable game/practice situation, the Canadian National assistant coach tossed the ball into the air to simulate a set, and the player attacked and spiked the ball. The players took off from the force plate as they would take off from a normal playing floor.

Following the spike jump take-off, a series of spike jumps were performed in which the landing kinematic and kinetic data were collected. The net position was adjusted for each player to allow a one-foot landing on the force platform. Again, only a few practice trials were needed until the landings of these top-caliber players consistently hit the force plate. Once the trials were completed for the left lower extremity, the right lower extremity was marked, and the players performed the jumps again.

Data Analysis

A motion analysis program (Kintrak; Motion Analysis Corp., Santa Rosa, CA, U.S.A.) quantified the kinematic data, kinetic data, and inverse dynamics of the lower limbs. The force plate data provided the maximal vertical ground reaction forces, and by means of the video data, the joint kinematics (hip, knee, and ankle) as well as the segmental kinematics (thigh, leg, and foot) were determined. Lower extremity joint moments were estimated with an inverse dynamics analysis, based on a rigid body model.[30] The video data and the force data were smoothed by a low pass Butterworth filter with a cut-off frequency of 25 Hz, and finite difference methods were used to calculate derivatives with respect to time.

Statistical Analysis

Each player had good quality data from two or three trials for each specific jump, and each player performed jumps in all four different categories: right limb take-off, right limb landing, left limb take-off, and left limb landing. The trials in each category were averaged for each subject, and the averages were entered into statistical analyses. The variables statistically analyzed were: dorsiflexion (DF) angle, plantarflexion (PF) angle, inversion angle, eversion angle, tibial internal rotation angle, tibial external rotation angle, dorsiflexor moment, plantarflexor moment, internal tibial rotation moment, external tibial rotational moment, inversion moment, and eversion moment.

Data were analyzed using a two-way analysis of variance (ANOVA) with repeated measures to compare differences between right and left limbs and take-off and landing (SPSS, Inc., Chicago, IL, U.S.A.). Significant interaction effects for the two-way ANOVA were analyzed post hoc using simple main effects. Logistic regression (BMDP, Los Angeles, CA, U.S.A.) gave direct estimation of the probability of a dichotomous variable (patellar tendon pain or no pain) from the multiple continuous variables.[31] In the stepwise procedure, the log likelihood was used (with improvement χ^2) to assess if a term entered or removed at that step significantly changed the prediction. The Hosmer Goodness-of-Fit Test[32] was used to evaluate the quality of the comparison between the observed clinical pain (or no pain) versus the predicted patellar tendon pain (or no pain). Statistical significance was set at $p \leq 0.05$, and all "differences" reported in the Results were statistically significant, unless otherwise noted. The data were presented as means ± standard errors (SE).

RESULTS

These members of the Canadian Men's National Volleyball team were right-handed and executed the spikes with their right hands. Each player wore the same, customary footwear. The 10 players (one of the initial 11 players withdrew part-way through the data collection session due to an unrelated injury) had an average age of 23.2 ± 0.8 years, height of 197.6 ± 1.9 cm, and body mass of 91.9 ± 1.2 kg. As this was the full National Team, subjects consisted of players of different positions (e.g., setters, outside hitters, and middle blockers). Upon interviewing and physically examining the players, 3 of the 10 players were diagnosed as having patellar tendinopathy at the time of testing. Three right knees and two left knees were diagnosed as symptomatic.

Ankle Joint Kinematics

The maximal angle of plantarflexion occurred at take-off for both limbs (Table 1 and Figure 1A). Maximal plantarflexion occurred during left-limb take-off. The maximal ankle plantarflexion on spike take-off was significantly larger for the left ankle than the right ankle.

TABLE 1. *Ankle joint angular maxima*

	RTO	LTO	RLD	LLD
DF	32.1°	9.5°	30.2°	26.6°
	(2.9)	(3.3)	(2.5)	(1.0)
PF	34.6°	39.2°	26.6°	35.3°
	(2.2)	(2.7)	(2.6)	(1.9)
INV	22.8°	–13.7°	13.4°	13.3°
	(3.1)	(1.3)	(1.3)	(1.4)
EV	16.1°	4.8°	8.0°	8.4°
	(2.6)	(2.5)	(2.8)	(3.0)
ExRot	16.6°	10.1°	13.0°	10.0°
	(1.6)	(3.5)	(2.1)	(2.4)
InRot	5.7°	16.6°	6.5°	11.8°
	(2.2)	(2.7)	(1.6)	(1.5)

See text for details of statistically significant differences.
Values in degrees (°) are means (± SE).
DF, dorsiflexion; RTO, right take-off; PF, plantarflexion; LTO, left take-off; INV, inversion; RLD, right landing; EV, eversion; LLD, left landing; ExRot, external rotation; InRot, internal rotation.

Players plantar-flexed more during the take-off phase of the jump than they did during impact during landing. Maximal ankle dorsiflexion occurred in the right limb during right limb take-off. A significantly larger amount of left ankle dorsiflexion occurred during landing than during take-off, with primary ankle dorsiflexion happening during landing of the jump. That was not the case for the right limb as there was no statistical evidence to suggest that there was more dorsiflexion at landing.

The maximal ankle inversion angle occurred during the jump take-off. During the spike jump, the right limb had a significantly greater ankle inversion during take-off (but not at landing) when compared with the left. During the jump take-off phase, the right foot experienced more inversion than the left, and maximal foot eversion occurred during midstance of the take-off phase of the jumps. During the spike jump, the right foot eversion was significantly larger than the left. During the landing phase of the jumps, left and right foot eversions were comparable.

Maximal tibial external rotation of the right ankle joint complex happened during the spike jump take-off (Figure 1B), and the maximal tibial internal rotation happened during the jump take-off for the left limb. Our data revealed no difference between the tibial external rotation for the right and left limbs during the jumps, but the left limb tended to have a significantly greater internal tibial rotation than the right limb.

Ankle Joint Complex Moments

The plantarflexion moment was the largest moment (up to 0.4 BWm) in this study and was 3–10 times greater than any other moment (Table 2). The peak plantarflexion moment was followed by a sustained plantarflexion moment in the landing phase of the spike jumps (Figure 2A). The ankle plantarflexion moment during take-off had a more bell-shaped profile (Figure 2B). With the right-handed hitters in this study, during the spike jump take-off the left ankle had a significantly greater plantarflexion moment than the right ankle. Also,

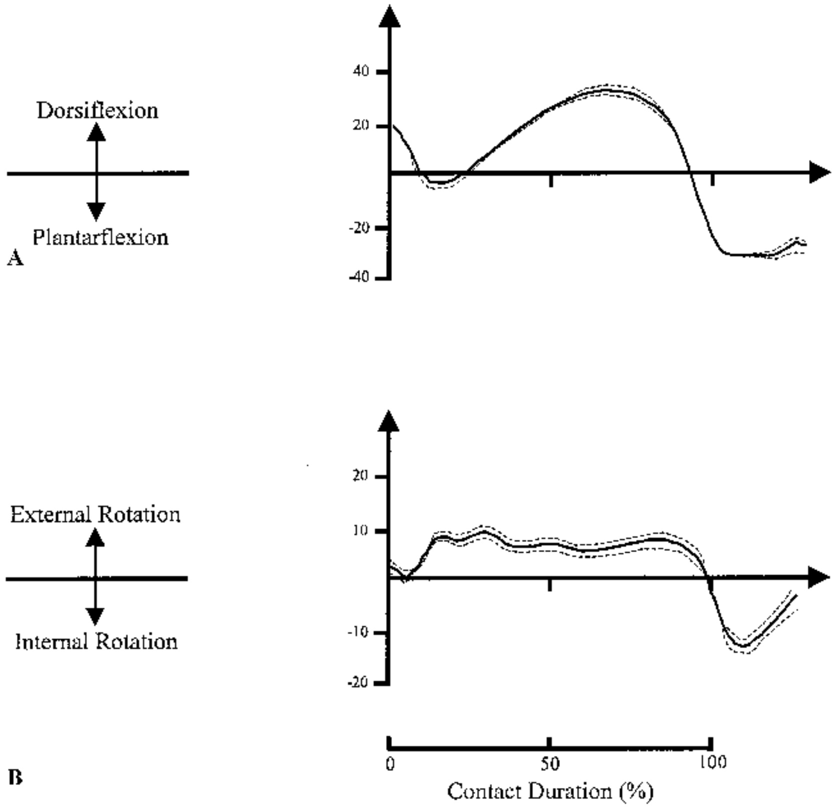

FIG. 1. Dorsiflexion/plantarflexion angles (**A**) and external tibial rotation/internal tibial rotation angles (**B**) in the right limb during the take-off phase of the spike jump. Solid lines represent the mean curves of all players, and the dashed lines indicate ± SE Contact duration is represented by 0–100%. Dorsiflexion and tibial external rotational angles are positive, and plantarflexion and tibial internal rotational angles are negative.

the right plantarflexion moment was significantly greater during landing than during take-off.

The maximal dorsiflexion moment occurred during the spike take-off for the right ankle. The magnitude of this moment was only 30% of the maximal plantarflexion moment and was the largest of all the other "non-plantarflexion" moments. The right ankle had a significantly greater dorsiflexor moment than the left during both spike take-off and landing. Ankle dorsiflexion moments were significantly greater for landing than for take-off.

The largest tibial internal rotational moment occurred in the left limb during landing from the spike jump. The largest tibial external rotational moment occurred in the left limb during the take-off phase of the spike jump. The maximal tibial external moments were greater than the maximal internal moments, except for the take-off phase with the right limb.

TABLE 2. *Maximal ankle joint moments (BWm)*

	RTO	LTO	RLD	LLD
DF	0.037 (0.007)	0.002 (0.009)	0.116 (0.032)	0.000 (0.014)
PF	0.277 (0.015)	0.398 (0.016)	0.352 (0.029)	0.373 (0.028)
INV	0.037 (0.004)	0.077 (0.021)	0.049 (0.013)	0.048 (0.011)
EV	0.039 (0.012)	0.024 (0.007)	0.086 (0.058)	0.058 (0.019)
ExRot	0.026 (0.008)	0.097 (0.011)	0.062 (0.018)	0.046 (0.009)
InRot	0.037 (0.064)	0.054 (0.017)	0.042 (0.010)	0.035 (0.008)

See text for details of statistically significant differences.

Values are in normalized units (BWm = body weight times meters); table contains means (± SE).

DF, dorsiflexion moment; RTO, right limb take-off; PF, plantarflexion moment; LTO, left limb take-off; INV, inversion moment; RLD, right limb landing; EV, eversion moment; LLD, left limb landing; ExRot, external rotation moment; InRot, internal rotation moment.

Logistic Regression

Logistic regression analysis revealed that only one of the biomechanical variables predicted the presence or absence of patellar tendon pain. During the landing of a spike jump the right foot inversion moment correctly predicted the presence or absence of right knee patellar tendinopathy ($p = 0.03$) in 100% of the right lower extremity cases. For all other kinematic and dynamics variables tested, no significant predictive relations existed with patellar tendinopathy.

DISCUSSION

Numerous analyses of the ankle joint complex have described ankle biomechanics from basic range of motion to kinematic kinematics.[2,22,33–44] Previously, we assessed the knee joint dynamics and their relation to patellar tendinopathy in this same group of elite volleyball players,[23] but that analysis did not include an assessment of the ankle joint complex and its potential link to patellar tendinopathy, as we have done here.

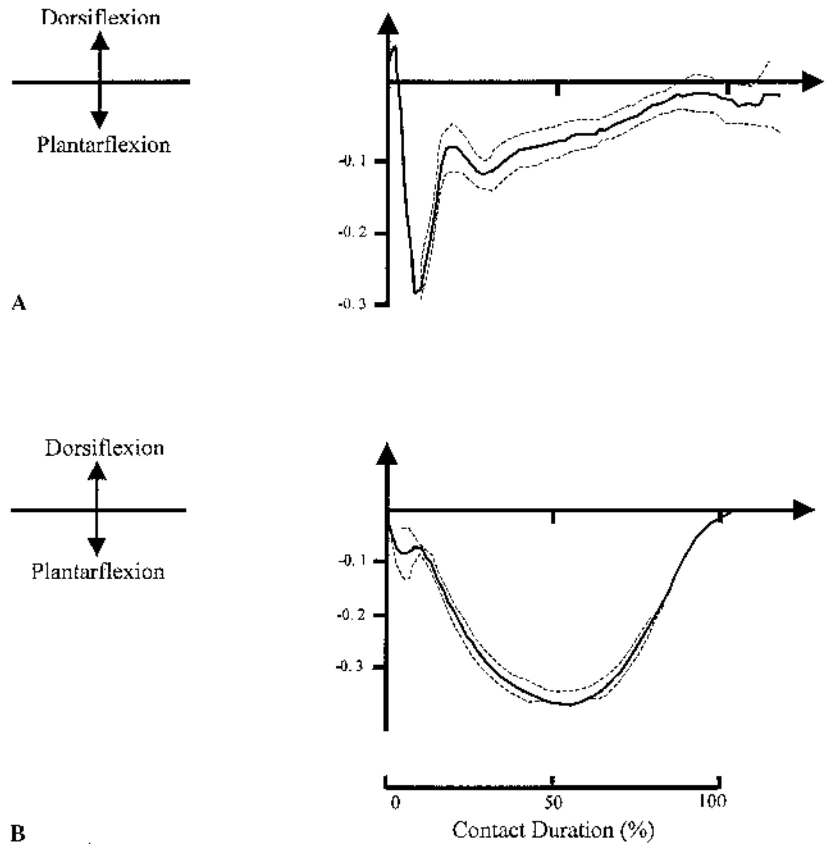

FIG. 2. Ankle joint plantarflexion moments. **A:** Right limb during landing; **B:** Left limb during take-off. Solid lines represent the respective mean curve of all players, and the dashed lines indicate ± SE. Contact duration is represented by 0–100%. Dorsiflexion moments are positive, and plantarflexion moments are negative. Moments are normalized to BWm.

Because of the high intensity of the spike jumps, the magnitudes of the kinematic and dynamic maxima from the current study were substantially greater than for walking and running. For example, in our study ankle dorsiflexion ranged from 10° (take-off, left) to 32° (take-off, right), and maximal plantarflexion ranged from 26.6° (landing, right) to 39.2° (take-off, left). This range was markedly greater than those reported by Sanmarco and colleagues[41] (46° maximal range; 23° in both dorsiflexion and plantarflexion), Dul and Johnson[35] (45°), or Winter[44] (30° during gait). In our study, players generated the greater range of ankle joint motion as maximal dorsiflexion coincided with deepest knee flexion during the jump preparation. Maximal plantarflexion happened at the instant of take-off and at first touchdown during landing.

For the right-handed player in our study, maximal right ankle inversion occurred during the jump take-off (23°). That value is similar to the 25° of inversion that Nigg[39] measured during running, and Leuthi and colleagues[22] reported during "shuttle" running (21–23°). The maximal eversion in our study (16°) occurred at the right ankle joint during preparation for the jump take-off. Thus, combining inversion and eversion, our maximal range of motion was 39°. The intensity of the spike jumps produced that greater inversion–version excursion, as the volleyball players had a larger total range of motion than those reported previously (e.g., Siegler et al.[42] [32°]; Hicks[36] [25°], Dul and Johnson[35] [24°]).

The tibial external rotation that occurred during the spike jumps ranged from 10° during left limb landing to 17° during right limb, whereas tibial internal rotation varied between 6° during right limb take-off and 17° during left limb take-off. Our peak tibial internal rotation was comparable to that measured by Nigg and colleagues[38] (22°). The total maximal change of tibial internal-to-external rotation was 33°, with the maximal range of tibial motion occurring in the left limb during the take-off phase (27°). That was substantially less than the total range of tibial rotation that Siegler and colleagues[42] measured (52°), but greater than was reported for walking.[45] In contrast to tibial rotation during walking[36,37] where external tibial rotation happens as the ankle is moved from dorsiflexion to plantarflexion, our study revealed that maximal external tibial rotation was sustained during maximal ankle dorsiflexion (compared with approximately 75% of contact duration during take-off phase, Figure 1), while maximal internal rotation coincided with maximal ankle plantarflexion (compared with immediately after take-off, Figure 1).

The ankle plantarflexion moments for the volleyball players were greater than those described for locomotion[2,40,43]; for example, for running, ankle plantarflexor moments have been reported to be 240 Nm versus the 360 Nm for the left ankle in the take-off phase of the volleyball spike jump. Similarly, the volleyball players had maximal ankle plantarflexion moments that were greater than two studies that measured ankle joint moments during jumping. Bobbert and colleagues[33] measured a peak plantarflexion moment of 150 Nm, and De Graaff and colleagues[34] measured plantarflexion moments up to 194 Nm during one-legged jumps.

The largest ankle dorsiflexion moment measured for the volleyball players was in the right limb during landing. That peak moment was 0.116 BWm (108 Nm), whereas the remaining dorsiflexor moments were markedly less. Reinschmidt and Nigg[40] measured an ankle dorsiflexor moment of 12.6 Nm during running, and that moment magnitude was comparable to the typical ankle dorsiflexion values during take-off and landing (except for the right ankle during landing).

In our earlier study,[23] we found a significant correlation between knee joint dynamics and patellar tendinopathy. Specifically, the likelihood of patellar tendon pain was linked to high forces and rates of loading in the knee extensor mechanism, combined with large external tibial torsional moments (including those during landing).[23] In our current analysis of ankle joint dynamics for the same volleyball players, we discovered that right foot inversion moment during landing was also a significant predictor of patellar tendinopathy. Combining several of the significant predictors from both the current ankle and previous knee analyses can provide insight into a potential mechanism for patellar tendinopathy. For example, the range of maximal ankle inversion to eversion moments was greatest during the landing phase of the spike jumps (peak inversion-to-eversion moment range = 0.135 BWm, Table 2). In addition, maximal external tibial rotation and plantarflexion moments were comparatively high during the landing phase of the jump. During the spike jump landing phase, we found that the maximal time derivative of knee extensor moment was a significant predictor of patellar tendinopathy, and the average peak vertical ground reaction force transmitted to each limb was greater than 5.5 BW.[23] Taken together, the following interrelated chain of limb dynamics is one mechanism that may contribute to patellar tendon loading during the landing phase of the volleyball spike jump: high range of ankle inversion–eversion moments, high external tibial rotation and plantarflexion moments, large vertical ground reaction forces, and high rate of extensor moment development at the knee.

CONCLUSIONS AND SUMMARY

Patellar tendinopathy is the most common injury in volleyball players, and it may limit or halt a player's participation.[5] Since there is an association between ankle joint complex dynamics and lower extremity overuse injuries,[1,46] and given the serious consequences of patellar tendinopathy and the potential relation between ankle and overuse syndromes, we investigated the ankle's dynamic role in the development of patellar tendinopathy. This study provided a quantitative analysis of the ankle joint complex dynamics during volleyball spike jumps and provided new insights into the links between movement dynamics and extant patellar tendon pain.

Coupling our current results on ankle joint complex dynamics with our previously published results of the relation of knee joint dynamics to patellar tendinopathy,[23] our data suggest that one combination of dynamics factors linked to patellar tendinopathy is a high range of ankle inversion–eversion moments, high external tibial rotation and plantarflexion moments, large vertical ground reaction forces, and high rate of extensor moment development at the knee.

These findings are limited and can only be applied directly to these 10 players, as we have an indeterminate "cause and effect" relation. From this study, we cannot discern whether the differences in jump dynamics were a consequence of the patellar tendinopathy or was the tendinopathy a consequence of the differences in jump dynamics? A longitudinal, prospective study of the jump dynamics of asymptomatic elite players will be important to confirm whether these predictive differences in dynamics successfully divide players into those who develop patellar tendinopathy versus those who remain asymptomatic.

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