Biomechanical Determinants of the Jumper's Knee in Volleyball

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ANKLE AND KNEE JOINT LANDING DYNAMICS IN VOLLEYBALL

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Abstract

In the search of the potential role of ankle and knee joint dynamics related to overuse injuries (e.g. patellar tendinopathy) in volleyball, there is a lack of normative reference data of ankle and knee joint dynamics during the volleyball jump and landing. This study provides sagittal plane ankle and knee joint landing dynamics of two different volleyball jumps (spike jump and block jump), and compares this with the landing dynamics of the countermovement jump.

Nine healthy high-level amateur male volleyball players participated in this study. Three dimensional inverse dynamics analyses were performed for the right limb using a three segment rigid body model. To compare the landing dynamics of the three jump types, a one-way ANOVA with repeated measures and simple contrasts were carried out.

Volleyball players performing a spike jump gained more jump height. During the landing phase this resulted in higher vertical ground reaction forces, higher ankle and knee joint angular velocities, higher loading rate of ankle and knee joint moments, greater ankle joint moments and a tendency of greater knee joint moments, and higher muscle energy absorption by the ankle plantar flexor and knee extensor muscle group compared to the countermovement jump. Block jumps showed smaller knee joint moments and smaller muscle energy absorption of the knee joint, compared to the countermovement jump.

A sagittal plane data set of ankle and knee joint landing dynamics in volleyball was given. Data analysis revealed that during the landing of the spike jump the athlete’s extensor mechanism sustained a higher load at the ankle and knee joint compared to the landing of the countermovement jump. Contrary, the landing of the block jump showed lower loads for the knee joint compared to the countermovement jump.

3.1. Introduction

To avoid injuries in volleyball, the kinetic energy generated from the spike and block actions, should be absorbed properly by the leg's extensor mechanism during landing. Repetitive high intensity loads during the jump-landing sequence can traumatize the quadriceps tendon (Blazina et al., 1973; Ferretti et al., 1990; Kujala et al., 1989; Lian et al., 2005; Pezzullo et al., 1992). Among high level volleyball players, the most frequent injury is patellar tendinopathy (jumper’s knee) with a prevalence of 40% to 50% (Lian et al., 2003; Lian et al., 2005). Besides the reduction in playing level, this injury often results in a reduced training load for long periods of time. In daily life, stair climbing and prolonged sitting can be problematic. Intrinsic factors, commonly associated with jumper's knee, are leg length discrepancy, pronation of the foot, muscular weakness and imbalance, and quadriceps and hamstring flexibility (Kannus, 1997). The extrinsic factors floor hardness and training volume also correlate with the prevalence of jumper's knee (Ferretti et al., 1990; Kannus, 1997).

To accommodate the impact during landing, lower extremity kinematics before and during impact phase influence the loads around the joints. By using joint moments of force and joint kinematics of the lower extremity, landing mechanics describe the efficiency of absorption of the kinetic energy from the jump. Because volleyball is a sport that requires many jump and landing movements, especially spike and block actions, the landing strategy used in these jumps is essential for optimized absorption of the energy. Many biomechanical studies have examined landing dynamics related to overuse injuries by evaluating the influence of height on impact forces or lower extremity joint dynamics in drop jumps (Caster & Bates 1995; Devita & Skelly, 1992; James et al., 2003; McNitt-Gray, 1991; McNitt-Gray, 1993; Santello & McDonagh, 1998). Supplementary, specific volleyball landing studies related to overuse injuries were carried out by Adrian & Laughlin (1983), who analysed vertical ground reaction forces of landings from block jumps in a female volleyball population. Tillman et al. (2004) quantified several jumping and landing techniques among elite female volleyball players in competitive matches by observations. In relation to patellar tendinopathy Lian et al. (2003) examined leg extensor characteristics among elite volleyball players using a jump and strength testing program.

Few studies actually used an inverse dynamics analyses approach to determine internal limb mechanics of the jump or landing movements in volleyball. Decker et al. (2003) used simulated block and spike jumps from a platform to distinguish gender differences in recreational athletes in lower extremity dynamics. In the study of Dufek & Zhang (1996), female elite volleyball players performed block landings to identify changes in landing impact mechanism across the season. Finally, Richards et al. (1996 and 2002) used an inverse dynamics approach while performing realistic volleyball jumps in their search for a relationship between ankle and knee joint dynamics and patellar tendinopathy in an elite male volleyball population.

Still, no complete data set exists of ankle and knee joint landing dynamics after both common volleyball jumps, spike and block jump. This paper provides sagittal plane data of ankle and knee joint motions and energy absorbing landing strategies of the right leg during maximally performed volleyball spike and block jumps among high-level amateur male volleyball players. The outcomes of these two volleyball jumps will be compared with landing dynamics of the well documented countermovement jump (CMJ), which is commonly used in the literature as a measure for examining jump performance and investigating the influence of the countermovement on force development to gain more jump height (Bobbert et al., 1996). In the present case, the CMJ acts as a reference jump.

3.2. Methods

Participants

Nine physically fit and well-trained male volleyball players participated in this study. The characteristics of this group were (mean ± standard deviation): age 24.3 ± 2.9 yr, body mass (BM) 80.6 ± 6.3 kg, height 190.0 ± 3.5 cm, leg length (l0) 99.9 ± 2.1 cm. All athletes participated in volleyball at least three times a week and had been competitive for at least 5 years at the third or second division of the Dutch volleyball competition. Participants had no recent injury history (three months) and had any surgery in the lower extremities and the back. Written informed consent was obtained from all participants prior to their participation and the study was approved by the local ethics committee. The participants followed a standardized warming-up and stretching period. During the measurements participants wore their own indoor sport shoes.

Procedures

Measurements were made of the right leg during landing of the CMJ, SPJ, and BJ after giving specific instructions to the participant. For each type of landing a series of five landings was performed. All jumps were executed according to the participant’s own preferred style, where during the spike jump all participants performed a three step and double footed take-off. Participants were allowed to practice before measurements took place. To minimize variability due to fatigue, participants had five minutes of rest between each series. A line was taped behind the force plate simulating the midline. Above this midline a cord was stretched at the official net height of 2.43 m. Data acquisition required that the participants landed with the right foot on the force plate. During their performance, participants were instructed to look ahead. Video registration was used to verify adequate landing on the force plate.

Data acquisition

Three dimensional position data of a 12 marker set (4 markers per set) were collected at 200 Hz using an Optotrak motion analysis system with two camera's containing three sensors each. Two molded rigid marker frames (3.2 mm Aquaplastic) on which 4 light emitting markers had been fixed, were tightly attached to the right thigh and shank with wide neoprene bandages and Velcro fasteners. Foot segment markers were attached to the shoe at the lateral side of the calcaneus. A Bertec force plate (type 4060-08) was used to measure the three components of the ground reaction force, and the three components of the external moment at a sampling rate of 1000 Hz. Position of the center of pressure was computed afterwards. After amplifying all force plate signals were converted to digital by the 16 bit A/D converter of the Optotrak system.

Prior to data collection a calibration measurement was carried out to determine the position and orientation of the underlying bone of the three segments, describing the anatomical coordinate system according to Cappozzo et al. (1995). For this procedure, the participant was standing in an erect posture so that all markers of the segment marker frames were visible. The position of the anatomical landmarks were measured using an Optotrak 6-Marker Probe.

Joint angles were calculated according to the method described by Grood and Suntay (1983) as suggested by the ISB (Wu & Cananagh, 1995), where knee extension and ankle dorsal flexion is positive. Anthropometric data for the estimation of segment mass, segment length, center of mass and radius of gyration of thigh, shank, and foot were calculated using data from de Leva (1996).

Data analysis

Three dimensional dynamic analyses were done for the right limb using a three segment rigid body model. A Matlab (The Mathworks, Inc; Version 6.5) based motion analysis program BodyMech (http://www.bodymech.nl, Free University Amsterdam) processed kinematic and kinetic data, and inverse dynamics was used to determine sagittal plane ankle and knee joint dynamics. For the comparison of the vertical ground reaction force (VGRF) characteristics, the force plate data was smoothed using a second order low pass zero phase Butterworth filter with a cut-off frequency of 100 Hz. For the assessment of ankle and knee joint moments, a cut-off frequency of 20 Hz was used for both force plate and kinematic data, as stated by Bisseling & Hof (2006). Start of the landing phase was defined as the moment when the VGRF exceeded 4 N. The calculation of joint moments, combining position data and force plate data, was based on the equations of motion as formulated by Hof (1992). Knee extensor and ankle dorsal flexor moments were assigned to be positive. Joint moments were presented in local joint coordinate systems, according to Grood & Suntay (1983) and Wu et al. (2002). Loading rate of the joint moments was defined as peak value of the first derivative of the moment curve.

Mechanical joint work was defined as the integral of muscular power during landing phase, which was defined as the time between touch down and the point at which the latter of either ankle or knee power curves crossed the zero intercept. Jump height was defined as the maximum difference in height between the great trochanter position during the jump and the height of the great trochanter during standing in an erect posture.

In order to reduce inter-subject variability, joint moments and joint work were scaled to $BM \cdot g \cdot l_0$, loading rate of joint moments were scaled to $BM \cdot g^{1½} \cdot l_0^{½}$, VGRF was scaled to $BM \cdot g$, and joint power was scaled to $BM \cdot g^{1½} \cdot l_0^{½}$ (Hof, 1996). Data were analysed using one-way ANOVA with repeated measures to determine the effect of the jump type on the biomechanical variable studied. Where significant effects were found ($p<0.05$), simple contrasts were used to determine whether SPJ or BJ differed significantly from CMJ. All differences reported in the Results were statistically significant, unless otherwise noted.

3.3. Results

The group mean values and standard deviations of jump height and sagittal joint kinematics during the landing phase, and statistical effects of the three jump types are presented in Table 3.1. Data of VGRF, sagittal joint kinetics and joint energetics during the landing phase, and statistical effects are presented in Table 3.2. All graphical representations are from the same participant.

Jump height

It appeared that jump height was significantly affected by the jump type (F(2,14) = 94.45, p<0.01). During SPJ participants gained a 0.09 m higher jump height than during CMJ. Contrary to the 0.04 m. lower jump height in BJ compared to CMJ.

Joint Kinematics

Ankle and knee joint angles from a representative participant are graphically represented in Figure 3.1. Where no effects were found of jump type on knee flexion at the time of touch down, F(2,16) = 1.13, p>0.05, they were found for ankle plantar flexion at the time of touch down, F(2,14) = 13.60, p<0.01. For both SPJ and BJ ankle plantar flexion was greater compared to CMJ (6 and 3 deg. respectively). Subsequently, no effect of the three jump types was found on maximal knee flexion during landing phase, F(2,16) = 3.23, p>0.05. Looking at ankle joint flexions during the landing phase, maximal ankle dorsiflexion was significantly affected by jump type, F(1.21,8.44) = 33.78, p<0.01. Compared to CMJ, both SPJ and BJ showed a reduced ankle dorsiflexion of 5.5 and a small 1.1 degrees, respectively. Despite the differences in maximal ankle plantar flexion at touch down and the ankle dorsiflexion during the landing phase, no effects of the three jump types were found on ankle range of motion (ROM), F(2,14) = 6.51, p>0.05. Knee ROM was significantly affected by jump type, F(2,16) = 4.26, p<0.05, but showed only a tendency of higher knee ROM for SPJ compared to CMJ. Instead, knee peak angular velocities were significantly affected by jump type, F(1.07,8.55) = 11.11, p<0.01. Higher values were found for SPJ, where lower values were seen for BJ compared to CMJ. The same effect was seen for ankle peak angular velocities, F(2,14) = 16.84, p<0.01, where SPJ showed higher values than CMJ.

Vertical ground reaction force

VGRF curves from a representative participant are graphically represented in Figure 3.2. The higher jump height in SPJ leads to higher impact velocities, which should have their effect on the GRF. Indeed, peak VGRF (F2 in Figure 2) was significantly affected by jump type, F(2,14) = 38.58, p<0.01, resulting in a larger peak VGRF during SPJ (p<0.01) compared to CMJ, and a tendency of smaller peak VGRF during BJ compared to CMJ.

Table 3.1 & 3.2. Mean (SD) values of jump height, joint kinematics (3.1 left table), normalized VGRF, sagittal ankle and knee joint kinetics and energetics (3.2 right table) performed during the countermovement jump (CMJ), spike jump (SPJ) and block jump (BJ).

	CMJ	**SPJ**	**BJ**
Jump height (m)			
	0.47	0.56 *	0.43 *
	(0.08)	(0.09)	(0.09)
Contact position (deg)			
Knee	-20.54	-17.83	-18.86
	(5.13)	(6.36)	(5.68)
Ankle	-30.89	-36.94 *	-33.76 *
	(5.81)	(5.46)	(5.59)
Maximum flexion (deg)			
Knee	-69.54	-73.18	-67.48
	(6.77)	(7.84)	(8.21)
Ankle	22.56	17.07 *	21.46 *
	(1.74)	(3.16)	(2.17)
Range of motion (deg)			
Knee	49.00	55.34	48.63
	(6.30)	(6.06)	(6.44)
Ankle	53.45	54.01	55.22
	(6.40)	(4.81)	(5.64)
Peak angular velocity (rad/sec)			
Knee	-3.72	-4.45 *	-3.45 *
	(0.36)	(0.63)	(0.40)
Ankle	7.04	8.13 *	7.00
	(0.82)	(1.14)	(0.89)

*Significant at $p<0.05$ between concerning jump variable and CMJ variable.
m, meter; deg, degrees; rad/sec, radians per second.

	CMJ	**SPJ**	**BJ**
Vertical GRF (norm)			
	3.040	4.460 *	2.720
	(0.190)	(0.620)	(0.390)
Peak joint moments (norm)			
Knee	0.259	0.292	0.226 *
	(0.037)	(0.068)	(0.044)
Ankle	-0.230	-0.275 *	-0.241
	(0.062)	(0.067)	(0.053)
Loading rate joint moments (norm)			
Knee	0.907	1.237 *	0.831
	(0.272)	(0.392)	(0.224)
Ankle	-1.354	-2.341 *	-1.231
	(0.393)	(0.684)	(0.359)
Peak joint powers (norm)			
Knee	-0.746	-1.005 *	-0.596 *
	(0.117)	(0.234)	(0.085)
Ankle	-1.003	-1.636 *	-0.934
	(0.308)	(0.359)	(0.147)
Negative joint work (norm)			
Knee	-0.110	-0.149 *	-0.097
	0.020	0.054	0.018
Ankle	-0.113	-0.149 *	-0.115
	(0.039)	(0.040)	(0.020)

*Significant at $p<0.05$ between concerning jump variable and CMJ variable.
norm: normalized data (see method section)

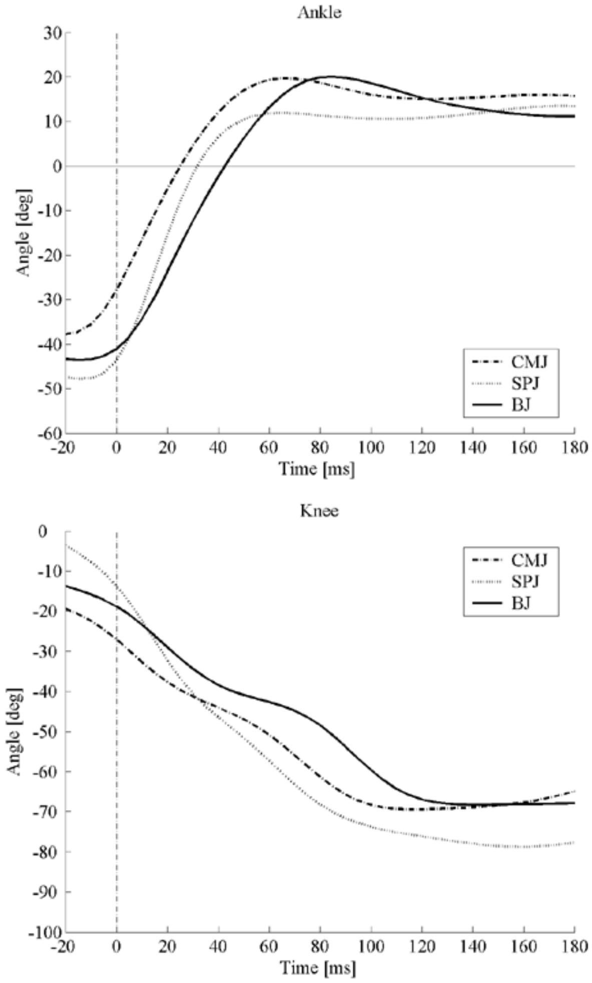

Figure 3.1. Ankle and knee joint angles during landing of CMJ (dash dotted line), SPJ (dotted line) and BJ (solid line). Negative values indicate knee flexion and ankle plantar flexion. Vertical line represents moment of touch-down.

Joint kinetics

Graphical representation of the joint moment curves from a representative participant can be found in Figure 3.3. As already appeared from peak VGRF data, ankle and knee joint peak moments were significantly affected by jump type, F(2,14) = 6.19, $p<0.05$; F(2,16) = 6.86, $p<0.01$, respectively. Where a tendency of higher knee joint peak moment values were found for SPJ compared to CMJ, higher joint peak moment values were found for the ankle joint. During BJ participants showed smaller knee joint peak moments compared to CMJ. A significant effect of jump type on the temporal characteristic joint moment loading rate was found for the ankle and knee joint, F(2,14) = 23.69, $p<0.01$; F(2,16) = 5.64, $p<0.05$, respectively. SPJ showed for both ankle and knee joint moment a higher loading rate compared to CMJ.

Joint energetics

Energy absorption values during landing showed significant effect of jump type on joint power (ankle: F(2,14) = 24.39 ,$p<0.01$, knee: F(2,16) = 21.30, $p<0.01$), and on joint work (ankle: F(2,14) = 5.02, $p<0.05$), knee: F(2,16) = 8.66, $p<0.01$). Participants showed higher knee peak power values during SPJ, and lower values during BJ compared to CMJ. Also in ankle power, highest values were generated during SPJ. Supplementary, the largest amount of knee joint work was executed during the landing phase of SPJ, and BJ showed a tendency of a smaller amount of knee joint work, compared to CMJ. Ankle joint work revealed no statistical differences between BJ and CMJ, but again in SPJ higher values were found compared to CMJ.

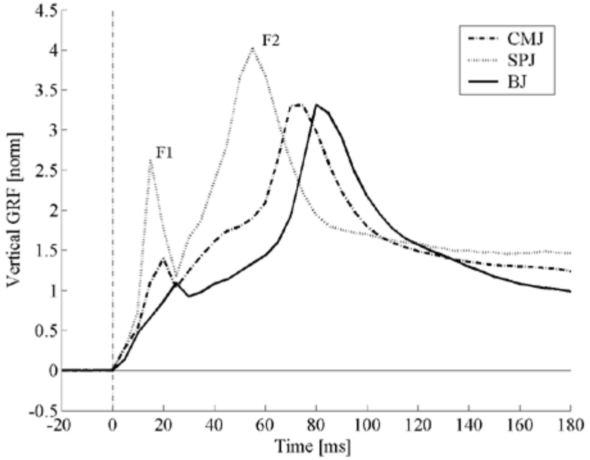

Figure 3.2. The VGRF during the landing of CMJ (dash dotted line), SPJ (dotted line) and BJ (solid line). Bi-modal force peaks F1 and F2 were evident from all participants. The Vertical line represents moment of touch-down.

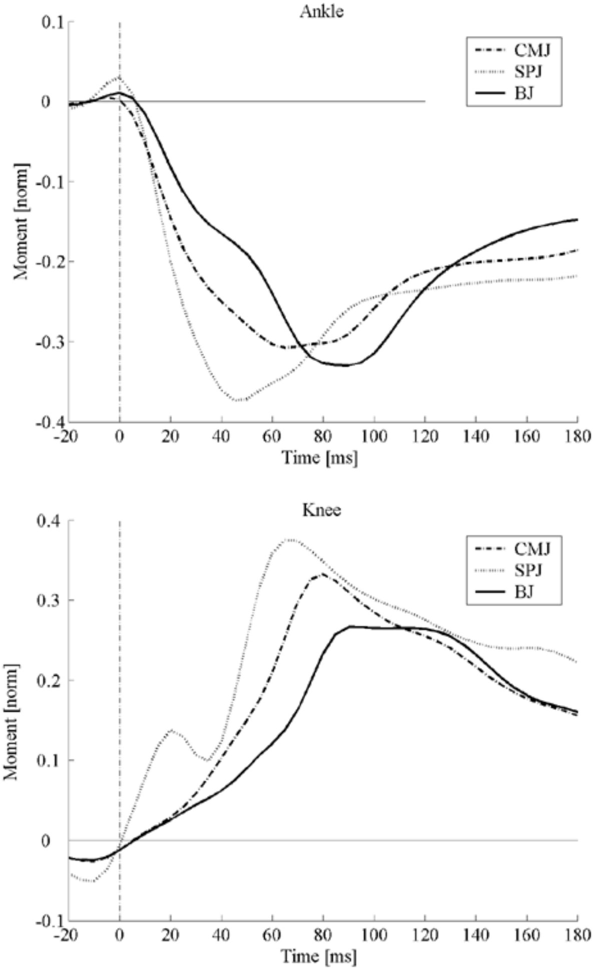

Figure 3.3. Sagittal ankle and knee joint moment during the landing of CMJ (dash dotted line), SPJ (dotted line) and BJ (solid line). Negative ankle joint moment corresponds with plantar flexion moment. Positive knee joint moment corresponds with knee extensor moment. Vertical line represents moment of touch down.

3.4. Discussion

This study was the first to provide a complete data set of ankle and knee joint landing dynamics of several volleyball jumps for healthy high-level amateur male volleyball players. The main finding was that during the landing of SPJ, the participants' extensor mechanism was exposed to higher loads and higher energy absorption than during CMJ, whereas the performance of BJ only resulted in lower energy absorption by the knee joint compared to CMJ.

Our data showed a higher jump height in SPJ, compared to CMJ and BJ. For comparison, Lian et al. (2003) reported mean CMJ heights of 0.41 m for jumper's knee patients and 0.40 m for controls. Dufek and Zhang (1996) found block jump heights of 0.33 m across the competitive season among elite female volleyball players. The advantage of the SPJ in gaining height compared to the CMJ and BJ is that during spiking the muscles are able to produce more work over the first part of their shortening distance, by reaching a higher level of active state and muscle force, probably due to the higher segmental velocities caused by the run-up of the SPJ (1996).

In our study, higher impact velocities due to higher jump height in SPJ cause nearly 50% higher peak VGRF values (Table 3.2) compared to CMJ. Several other studies have reported VGRF characteristics during volleyball movements. Adrian and Laughlin (1983) reported average peak VGRF of 3.0 to 3.7 times BW (body weight) during the landing of a stationary and a moving block, respectively, among 15 elite female volleyball players. Dufek and Zhang (1996) reported average peak VGRF ranging from 2.07 to 2.51 times BW during the landing phase of a block landing in elite female volleyball players. During simulated block and spike landings from a 60 cm high platform Salci et al. (2004) reported mean peak VGRF values ranging from 3.9 to 4.4 times BW, respectively. In a study quantifying lower limb dynamics during volleyball spike and block jumps among elite male volleyball players related to patellar tendinopathy, Richards et al. (1996) found mean VGRF ranging from 2.8 to 3.0 times BW for left and right leg respectively in block landings, and 5.6 to even 6.0 times BW for right and left leg respectively, during spike landings. Considering the difference in population studied by the investigators, peak VGRF during block landings and spike landings found in literature are in line with our presented data (Table 3.2). While we studied landing dynamics of non-elite athletes (third or second division of the Dutch volleyball competition), Richards et al. (1996) investigated landing dynamics of elite male volleyball players, which probably resulted in higher jump heights causing greater impact forces.

Our presented joint angles showed similar results with reported joint landing kinematics during volleyball jumps by Richards et al. (1996 and 2002) and Salci et al. (2004). In agreement with our results, research has shown a tendency that the amplitude of foot plantar flexion at initial contact and dorsiflexion angular velocity during the landing phase increased with fall height, where the amplitude of ankle ROM remained constant across heights (McNitt-Gray, 1991; Santello & McDonagh, 1998). Because knee ROM only shows a tendency of higher values for SPJ compared to CMJ and knee peak angular velocities were higher during SPJ, corresponding with higher peak angular velocities of the ankle, it is reasonable to suggest that participants after a SPJ land with stiffer ankle and knee joints. This stiffer landing should result in a greater loading rate of the ankle and knee joint moment. Indeed, the results of the temporal characteristics of the joint moment in SPJ landing showed the highest loading rate for ankle plantar flexion and knee extension moment. This same pattern was seen in the loading rate of VGRF. Stiffness of the joints effects the transmission of potentially harmful impact shocks in a distal-proximal sequence. Shock attenuation during landing is the process of absorbing impact energy and reducing the amplitude of the shock wave (or force rate of loading), which is hypothesized to be related to overuse injuries (Nigg et al., 1995).

SPJ landing calls for the highest energy absorption and therefore makes the quadriceps extensor mechanism (e.g. patellar tendon) more vulnerable. For the average joint power and work, it seems that the ratio of energy absorption by the ankle and knee joint during BJ differs from SPJ and CMJ. Compared to CMJ, BJ ankle joint work remained constant, where knee joint work tended to decrease, while in SPJ both ankle and knee joint work increased. The same pattern can be seen in the peak joint moments. It can thus be stated that different landing techniques were used during SPJ, BJ and CMJ.

A measure for joint load during an activity is joint moment. We found greater ankle joint moments and a tendency of greater knee joint moments during the landing phase of SPJ (Table 3.2). For comparison, Richards et al. (2002) found ankle plantar flexion moments of 0.35 BW•m (body weight times meter), and knee extension moments of 0.43 BW•m and 0.26 BW•m in respectively spike landings and block landings (Richards et al., 1996). An explanation of these higher values compared to our joint moment values, assuming that their data were normalized for leg length (m), can be found in the different population studied, as already mentioned at the VGRF section of this discussion. Another explanation might be found in the method used to determine joint moments. In a previous study (Bisseling & Hof, 2006), to improve the inverse dynamical method for the assessment of knee moment, it was shown the impact peak around 20 ms found in the knee moment, calculated using a standard inverse dynamical method, was an artifact. To overcome this problem it was proposed to use the same cut-off frequencies for both ground reaction force and calculated accelerations. The joint moments presented above were assessed with this new method. Therefore, precaution should be taken to compare our knee moment data with earlier knee moment data.

A normalized data set of ankle and knee landing dynamics in volleyball among well trained healthy high level amateur athletes is presented in the need for a complete reference data set of the dynamics of volleyball jumps. We found a 50% increase of VGRF in landing of SPJ, higher joint angular velocities, greater joint moments and loading rates of joint moments, and more energy absorption in the extensor mechanism compared to the CMJ. BJ showed smaller knee joint moments and energy absorption of the knee joint, compared to CMJ. A complete data set is essential for future studies to get more insight into the role of joint dynamics in the development of chronic sports injuries at the quadriceps mechanism (e.g. patellar tendinopathy).

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