Can kinematic and kinetic differences between planned and unplanned volleyball block jump-landings be associated with injury risk factors?

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Abstract

Introduction: Injury prevention programs for athletes are still limited by a lack of understanding of specific risk factors that can influence injuries within different sports. The majority of studies on volleyball have not considered the movement patterns when moving in different directions or in planned and unplanned block jump-landings.
Methods: This study investigated all planes mechanics between the lead and trail limb when moving in dominant and non-dominant directions, for both planned and unplanned jump-landings in thirteen semi-professional female volleyball players. Ankle, knee and hip joint kinematics, kinetics and joint stiffness were recorded.
Results: Our results showed statistically significant differences between the lead limb and the trail limb in the hip flexion angles, moments and velocity; in the knee flexion angles, moments, stiffness, power and energy absorption and in the ankle dorsiflexion, power and energy absorption, showing a tendency where the lead limb has a higher injury risk than the trail limb. When considering planned versus unplanned situations, there were statistically significant differences in knee flexion angles, moments, power and energy absorption; and hip contact angle,

flexion angular velocity and energy absorption, with musculoskeletal adaptations in the planned situations.
Discussion: It appears that the role of the limb, either lead or trail, is more important than the limb dominance when performing directional jump-landings, with the lead limb having a higher implication on possible overuse injuries than the trail limb. Furthermore, planned movements showed a difference in strategy indicating greater implications to possible overuse injuries than in the unplanned situations which may be associated with more conscious thought about the movements.
Conclusion: Coaches should consider unilateral coordination training in both landing directions for the lead and trail limb, and should adapt training to replicate the competition environment, using unplanned situations to minimize asymmetries to might reduce injury risks.

Keywords: *lower limb, unplanned, landing direction, jump-landing, technique*

Introduction:

Athletes endure physiological, physical and psychological stresses, all of which can be associated with injury risks [1]. The combination of specific tasks in volleyball with fast approach movements puts a great demand on the musculoskeletal system [2]. However, prevention programs are still limited by a lack of understanding of the specific risk factors that can influence injuries within different sports [3]. The knee joint has been reported as having the highest percentage of all lower limb injuries, especially in physically active populations [4, 5], with overuse being identified as the main cause [6]. It is therefore necessary to increase our understanding about the risk factors associated with knee injuries within volleyball.

Injury to the anterior cruciate ligament (ACL) is one of the most devastating and frequent injuries of the knee [7]. In volleyball, ACL injuries can occur when landing from a jump, for example when players move from the middle of the court to block a spike [8]. Stiff landings can be characterized by an initial contact with the ground with the joints of the lower limb being in a flexed position, which is followed by only small amounts of additional flexion during the deceleration phase [9]. A knee flexion angle of less than 30 degrees has also been shown to increase the ACL load during landing [10], with the highest peak load occurring approximately 40 ms after landing [11]. Also, there are some factors which significantly increased ACL strain and increase the risk of ACL injury, these include greater internal or external rotations of the knee [12], a single-leg landings [13] or a higher valgus loading of the knee joint [14]. Norcross et al., [15] found a greater sagittal plane power absorption during the initial contact phase, which indicates greater ACL loading. Angular velocities have also been suggested as measures of control of the knee joint [16], and have also been related to force generation and muscle activation [17].

In volleyball, only a small change in the contextual situation can cause the player to have to modify their movement patterns [18], one example of this is a response to an unpredictable or unplanned situation such as a change of direction to block a shot. However, the majority of studies that have considered the movement patterns during tasks associated with injury risk factors have not considered the uncertainty and speed of the real game due to difficulties in controlling such factors in a laboratory situation. Most interventions, whose principal aim is to improve motor control in order to reduce the incidence of injuries during sports games, are through training using isolated tasks [19]. However, injuries very seldom occur while performing an isolated task in a predictable environment, but occur more in unplanned environments. Leukel et al. [20] showed that muscle activation patterns are modified in unplanned situations when compared to situations when the subjects are planned about what task they have to execute. The question of what an expert athlete should focus their attention on when performing their skill has long been of interest [21]. It has been suggested that expert athletes perform better when their attention is focused externally in comparison with when their attention is focused internally [22]. This may also be relevant when considering unplanned movements being associated with unconscious or automatic processes and planned associated with a more conscious type of control that constrains the motor system and disrupts automatic control processes, as it focuses the athlete's attention on her own body movements [23].

Previous studies have identified limb dominance [24, 25] and lateral directional movements [26, 27] as important factors when considering knee injury risks. Side to side differences in the movement of the lower extremities has been considered an injury risk, although asymmetries occur in healthy individuals as well [28]. The development of side to side differences in the lower extremity and limb dominance in an athlete can stem from strength differences [29], incomplete or improper recovery from an injury [30, 31] or repetitive use of a limb for a task [32]. When a volleyball player is trying to get the greatest spike performance they use a natural sequence of a three-step technique during the jump which is determined by the dominant hand to favour the kinetics of the hit [33]. In this way, players tend to land with their non-dominant limb when they are performing a spike. For example, for a right-handed player, her usual step pattern during a spike should be left-right-left, which should be the same pattern than a block jump-landing when is moving to the left side (moving to zone IV), and thus moving to the dominant direction. Contrarily, if this player is moving to the other side (moving to zone II) during a block, her usual step pattern should be right-left-right, and thus moving to the non-dominant direction. However, when players are performing a block jump-landing depending on the direction of movement, which in turn depends on the game, they may have to change their natural three step technique, and therefore their jump-landing movement strategy. Therefore, it is necessary to promote balanced motor patterns (sports technique) that can help prevent injury through early detection of risks, which may be used in the planning of preventative programs.

For these reasons, the study of the risk factors in situations that approximate the characteristics of real movements during competition and training is relevant. Therefore, demands on the velocity, distance of jumping and uncertainty within the tasks, combined with limb and direction dominance are factors that are necessary for a more complete analysis and understanding of joint movements. Therefore, the purpose of this study was to investigate mechanics between dominant and non-dominant limbs when moving in dominant and non-dominant directions, for both planned and unplanned block jump-landings. We hypothesized there would be different strategies between limbs in all planes depending on if an individual lands in a dominant or non-dominant direction. Furthermore, we hypothesized that there would be differences between planned and unplanned situations.

Methods

2.1. Study Design

This study was a within-subjects design where the independent variables were: 1) a natural block approach when moving in different directions with 2 levels: a) the dominant direction, and b) the non-dominant direction; 2) limb dominance, with 2 levels: a) the lead limb, and b) the trail limb; and 3) planned/unplanned situations, with 2 levels: a) planned block jump-landing, and b) unplanned block jump-landing. The dominant direction was considered as the direction in which the participant performed their normal three-step sequence used when performing a volleyball spike. The dominant limb was determined as the preferred leg to kick a ball [34], which was the same as the preferred arm, with twelve right-handed and one left-handed players. Moreover, the lead limb was defined as the exterior limb during the jump-landing with the trail limb being the interior limb.

In this paper, we considered planned and unplanned situations before the start of the block approach. In this context planned refers to allowing time for conscious planning, whereas unplanned refers to the initiation of the block approach immediately on the cue of one of the three lights offering no time for conscious planning. The landing biomechanics were analysed to see if there were differences in movement strategies between “planned” and “unplanned” situations during landing. In both situations participants were asked to arrive at the net as fast as possible. These situations correspond to learning exercises of the ball-free blocking technique that are frequently used in volleyball. However, in the unplanned situation the player has three possible attacks which are displayed randomly and their task was to move and block them in the shortest possible time. This situation corresponds to a strategy of the game that is called "optional block" and consists of defending a "first time attack" reading blocking system (waiting to see the set) where one of the side attacks is prioritized. This tactical strategy is frequently used by central blockers, since they have difficulty to defend serving all possible attack positions. In addition, the lateral blocker can be located in a more central position to be able to defend against the “first time attack” and, if necessary, assist the side that corresponds to a “second time attack”. (Figure 1).

*** Figure 1 near here.

2.2. Subjects

Thirteen semi-professional female volleyball players who played in a national league were recruited from a university team (aged 20.43±2.17 years; height 171.24±3.3 cm; mass 65.65±6.34 kg). None of the subjects had any history of hip, knee or ankle surgery within the previous 6 months. The study was approved by the Ethics Committee for Human Research at the University of Granada. Prior to testing, the aims of the study and the experimental procedures were explained to the participants who then signed an informed consent form.

2.3. Experimental Setup

Ground reaction force data were collected at a sampling rate of 250 Hz using two force plates (9260AA Kistler Instruments, Hampshire, UK) embedded in the floor. Synchronously, an eight camera Oqus motion capture system (Qualisys, Sweden) was used to collect kinematic data at a sampling frequency of 250 Hz. Twenty-one retro-reflective markers were placed on each subject prior to data collection [35].

In order to create the unplanned jumps, participants performed a FitLight Trainer™ sequence programming protocol (Fitlight Sports Corp., Canada). This allowed a light sequence which was used as a target to create visual reaction information to the player, such as showing the blocking direction, whilst checking that the block has been made at the correct height.

2.4. Protocol

The experimental setting was based on a real game situation with the upper edge of the net set at 2.24m. To normalise the height of the jump, in unplanned situations the three Fitlight discs were suspended in the space located 0.20 m above the edge of the net and on the opponent's side of the court, which were used to simulate an attack and to determine if the block was effective [25]. Participants were asked to arrive at the net as fast as possible in both, planned and unplanned situations, with the difference that in planned situations the participant could begin when they wanted without any time pressure, allowing time for conscious planning. In unplanned situations there was uncertainty as the participants had to initiate their block movement as soon as one of the three lights was switched on, allowing no time for conscious planning of their movement. In addition, in unplanned situations, to block the three Fitlights which simulated attacks the participants had to perform: 1) a frontal jump, 2) a short lateral jump, and 3) a three-step block approach (Figure 1). Additionally, the time taken for a player to turn off the lights was used as a biofeedback to motivate the players, but this was not recorded. The evaluator only accepted trials when the movement was as fast as possible and additionally in unplanned situations the light was turned off. In addition, the evaluator assessed if both limbs landed on the force platforms, but care was taken to explain to the participants that they were not to target the plates. However, during the analysis with Qualisys Track Manager, the flight time of each jump in both situations was recorded and no significant differences in time were found between the planned and unplanned situations.

Each trial represents one block jump-landing and six successful jump-landings were recorded under each situation and each direction. All trials which did not accomplish these characteristics were discarded. The two force plates were embedded in the floor, and the Fitlight discs were placed so that in a normal jump the players landed on the two platforms.

The participants performed the tests in a single session during the course of 1 day. Before data collection, all subjects performed a 20 minute warm-up consisting of stretching the lower and upper extremities. Five training attempts followed the warm-up. At the start of each trial, the subject performed block jump-landings, from the left or right side, the direction of which was randomized. The participants were informed that they had to go at full speed and block the simulated attack. After each sequence a rest period of 5 minutes was allowed, and then the protocol was repeated in the opposite direction. Participants then performed block jump-landings using a blinded randomised sequence of attacks. Thus trying to simulate a real game context with block spikes from both sides, simulating moving to zone II and to zone IV of the court (Figure 1).

Fatigue was assessed using the Borg scale (6-20) after each sequence which was controlled so that it remained under a threshold of fifteen.

2.5. Data and statistical analysis

The marker data were processed using Qualisys Track Manager (QTM, Qualisys Inc., Gothenburg, Sweden) and exported into c3d format. Visual3D (C-Motion, Inc., Rockville, MD, USA) was used to calculate the three dimensional ankle, knee and hip kinetics and kinematics. The start of each trial was determined by the first occurrence of a ground reaction force > 20 N on each force plate, and the end was defined by the maximum flexion of each knee. The joint stiffness was calculated by the change of moment divided by the change of angle using the formula [$kj = \Delta M/\Delta\theta$] following Mager et al. [36], and the power absorption was calculated using [Power = Moment x angular velocity] and the energy absorption as the integral of power. The stiffness, power and energy absorption were only calculated for the sagittal plane.

All the data showed a normal distribution according to the Shapiro-Wilks test. 2 x 2 repeated measures analysis of variance (ANOVA) tests were used to explore the differences between dominant/non-dominant directions and planned/unplanned tasks on the dominant and non-dominant limbs separately. Further post hoc tests were performed using a Bonferroni correction to reduce Type I error, with the alpha level set to 0.05. IBM SPSS Statistics 22 software was used for all statistical tests (SPSS, Inc., and IBM Company, Chicago, IL).

Results

Kinematic and kinetic variables for the non-dominant hip, knee and ankle joints during the block jump-landing are shown in Table 1. For the non-dominant limb, there was a significant difference in the hip, knee and ankle angles between dominant and non-dominant directions with the non-dominant direction showing greater flexion in the hip ($F(1,12) = 9.204$, $p = .010$, $\eta^2 = .119$) and knee joints ($F(1,12) = 6.765$, $p = .022$, $\eta^2 = .364$), and a greater amount of plantarflexion at initial contact ($F(1,12) = 5.600$, $p = .036$, $\eta^2 = .318$). Significantly greater peak hip ($F(1,12) = 9.810$, $p = .009$, $\eta^2 = .450$) and knee flexion moments ($F(1,12) = 9.096$, $p = .011$, $\eta^2 = .431$) and ankle dorsiflexion moment ($F(1,12) = 9.372$, $p = .010$, $\eta^2 = .439$) were seen in the movements in the dominant direction, with greater peak hip ($F(1,12) = 10.468$, $p = .007$, $\eta^2 = .466$) and knee power absorption ($F(1,12) = 13.988$, $p = .003$, $\eta^2 = .538$), and significantly greater energy absorption at the knee ($F(1,12) = 15.544$, $p = .002$, $\eta^2 = .564$) and ankle ($F(1,12) = 11.319$, $p = .006$, $\eta^2 = .485$) when moving in the dominant direction. Peak hip flexion angular velocity was significantly greater in the non-dominant direction ($F(1,12) = 8.059$, $p = .015$, $\eta^2 = .402$), and lower peak joint stiffness was seen in the knee ($F(1,12) = 21.654$, $p = .001$, $\eta^2 = .643$) and ankle ($F(1,12) = 17.518$, $p = .001$, $\eta^2 = .593$), with a trend toward significance in the hip ($F(1,12) = 4.476$, $p = .056$, $\eta^2 = .272$).

For the knee power absorption and knee energy absorption there were differences between planned and unplanned tasks ($F(1,12) = 11.794$, $p = .005$, $\eta^2 = .496$) and ($F(1,12) = 7.700$, $p = .017$ $\eta^2 = .391$), with greater values in the planned movements. A statistically significant interaction was observed for the peak knee flexion moment ($F(1,12) = 34.476$, $p < .001$, $\eta^2 = .742$), further analysis showed a statistically greater knee moment in the dominant direction ($F(1,12) = 22.903$, $p < .001$, $\eta^2 = .656$). However, the peak knee flexion moments decreased with unplanned movements in the non-dominant direction (F(1,12) = 8.025, p= .015, η^2= .401), and increased in the unplanned movements in the dominant direction (F(1,12) = 8.447, p=.013, η^2= .413).

*** Table 1 near here

Kinematic variables for the dominant hip, knee and ankle joints during the block jump-landing are shown in Table 2. These showed a similar response to the non-dominant limb, with significantly greater flexion in the hip (F(1,12)= 5.316, p=.002, η^2=.561) and knee joints (F(1,12)=15.368, p=.002, η^2=.562) when moving to the dominant direction, however no significant difference was seen in the ankle joint at initial contact. The flexion moments also showed a similar response with greater peak hip (F(1,12)=12.505, p=.004, η^2=.510) and knee flexion moments (F(1,12) = 23.523, p< .001, η^2= .662) and ankle dorsiflexion moment (F(1,12)=10.585, p=.007, η^2=.469), with greater peak knee and ankle power absorption (F(1,12)=12.609, p=.004, η^2=.512; F(1,12)=6.048, p=.030, η^2=.335) and energy absorption (F(1,12)=24.207, p<.001, η^2=.669; F(1,12)=13.074, p=.004, η^2=.521) respectively, when moving in the non-dominant direction. Peak hip flexion angular velocity was significantly greater in the dominant direction (F(1,12)=20.682, p=.001, η^2=.633), with a lower peak knee joint stiffness (F(1,12)=8.276, p=.014, η^2=.408).

A statistically significant interaction was observed for the hip angle at contact (F(1,12)=4.828, p=.048, η^2=.287), showing a lower angle in the non-dominant direction for the planned landings (F(1,12)=7.541, p=.018, η^2=.386). Further analysis showed that there was a significant difference in the contact hip angle (F(1,12)=6.224, p=.028, η^2=.342) between planned and unplanned landings, showing a greater angle in unplanned landings, with greater peak knee flexion and peak flexion moment in the planned landings (F(1,12)=6.656, p=.024, η^2=.357; F(1,12)=6.024, p=.030, η^2=.334, respectively). Moreover, a statistically significant interaction was seen in the peak hip power absorption (F(1,12)=5.745, p=.034, η^2=.324). It was found that the power absorption decreased with unplanned movements in the non-dominant direction (F(1,12)=5.037, p=.044, η^2=.296) but increased in the planned movements in the dominant direction (F(1,12)=4.800, p=.049, η^2=.286), with greater hip energy absorption in the unplanned landings (F(1,12)=5.801, p=.033, η^2=.326),whereas the knee showed lower energy absorption in the unplanned landings (F(1,12)=5.252, p=.041, η^2=.304). A significant interaction was also seen in the peak ankle dorsiflexion angular velocity (F(1,12)=18.336, p=.001, η^2=.604), with the highest peak in the dominant direction and the lowest in the non-dominant direction.

*** Table 2 near here

Kinematic and kinetic variables for the dominant and non-dominant knee in the coronal and transverse plane are shown in Table 3. There were significant differences in the peak knee valgus (F(1,12)=15.514, p=.002, η^2=.564), the contact angle (F(1,12)=13.591, p=.003, η^2=.531) and the contact knee angle in the transverse plane (F(1,12)=6.621, p=.024, η^2=.356) between dominant and non-dominant directions with the non-dominant direction showing greater valgus knee angle. A statistically significant interaction was observed for the knee valgus angle (F(1,12)=10.567, p=.007, η^2=.468), showing a lower angle in the non-dominant direction for the unplanned landings (F(1,12)=7.584, p=.017, η^2=.387). Significantly greater peak knee valgus moment (F(1,12)=13.823, p=.003, η^2=.535) were seen in movements in the dominant direction. For the knee internal rotation moment differences were seen between planned and unplanned tasks (F(1,12)=6.258, p=.028, η^2=.343). Additionally, significant interactions were observed for peak knee internal rotation angular velocity ($F(1,12)=6.713$, $p=.024$, $\eta^2=.359$), showing higher values in planned tasks in the dominant direction.

For the dominant knee there was a significant difference in the peak knee valgus ($F(1,12)=16.742$, $p=.001$, $\eta^2=.582$), between dominant and non-dominant directions with the dominant direction showing a greater valgus knee angle. Greater peak knee valgus moments were seen when moving in the non-dominant direction compared with the dominant direction ($F(1,12)=13.052$, $p=.004$, $\eta^2=.521$). A significant interaction was observed for the peak ($F(1,12)=8.596$, $p=.017$, $\eta^2=.389$) and contact internal rotation angle ($F(1,12)=10.314$, $p=.019$, $\eta^2=.379$), showing a lower angle in the non-dominant direction in the planned landings ($F(1,12)=12.338$, $p=.004$, $\eta^2=.507$). However, higher peak knee internal rotation moments ($F(1,12)=19.903$, $p=.001$, $\eta^2=.624$) were seen in the movements in the non-dominant directions compared with the dominant direction

*** Table 3 near here

Discussion

The results of this study suggest that there were different strategies between the lead limb and trail limb when participants performed a block jump-landing, showing a tendency where the lead limb may have a higher implications on possible overuse injuries than the trail limb. Furthermore, planned situations may have greater musculoskeletal implications than unplanned situations. This highlights the importance of considering not only the lead and trail limb, but also the necessity to create situations as similar as possible to that of competition during training.

There are controversies about lower limb symmetry during landing tasks. Some authors reporting that there are no differences between limbs [37-39] and others reporting asymmetries. In agreement with Sinsurin et al. [26], we observed a similar response in the hip and knee joint angles for both limbs, with the trail limb having higher flexion angles with the ankle in less plantarflexion, therefore reducing the possible power absorption at the ankle. Skazalski et al. [40] showed that landing-related ankle injuries mostly result from rapid inversion without a substantial plantarflexion. However, the opposite response occurs when the peak dorsiflexion joint moments, power absorption and stiffness are considered. Zahradnik et al. [25] suggested that greater knee moments and power absorption present a greater risk of injury during the impact phase. Hinshaw et al. (2018) showed increased knee valgus moments and internal rotation angles for the lead limb [41]. For these variables, the trail limb had lower values, and consequently the lead limb may have the higher injury risk. In addition, the knee and ankle joints on the lead limb showed greater energy absorption, which could be related to the lead limb being the external limb and consequently taking greater loads during landing. Thus, our results may suggest that the limb with more injury risk is the lead limb, independent of whether it is the dominant or non-dominant limb. Moreover, the previous asymmetries due to strength, repetitive skills and the strategies could increase the magnitude of these differences.

Leukel et al. [20] confirmed that when there is an unplanned situation during a jump or landing, muscle activity and tendomuscular stiffness was reduced. The comparison of planned and unplanned three-step block jump-landings showed, for the non-dominant limb, the peak knee power absorption and the knee energy absorption were greater in planned than in unplanned jump-landings. In planned landings, energy absorption at the hip decreases with an increase in angular velocity on the dominant side. Additionally, for the dominant knee, the peak flexion angle and moment, the energy absorption, and the peak internal rotation tibial moment and angular velocity were greater in planned situations, indicating greater implications to possible overuse injuries. Moreover, the knee on the dominant limb had a greater flexion moment during planned compared to unplanned landings. According to Wulf, McNevin, and Shea [42] "when performers use an internal focus of attention (focus on their movements) they may actually constrain or interfere with automatic control processes that would normally regulate the movement". This could be explained by restrictions in the "Top - Down" system [43] in reference to the mechanism of neuronal activation for discrimination of relevant information when preparing a goal-oriented response. A possible explanation could be due to planned movements using an internal focus which changes the movement strategies, whereas in unplanned movements the volleyball players had an external focus. An external focus on the movement promotes the utilization of unconscious or automatic processes, whereas an internal focus results in a more conscious type of control that constrains the motor system and disrupts automatic control processes [44], and focuses the athlete's attention on his or her own body movements [23].

This current study created a protocol that integrated the majority of all planes variables that have been previously reported as risk factors in lower limb injuries. In addition, we considered both velocity and approach distance under the different situations, which provided greater ecological validity to the real game situation of performing block jump-landings [45]. Notwithstanding, this study did have some limitations; firstly, we only measured women from the same volleyball team with the same block jump-landing technique, secondly we only considered lower limb movements in the analysis, and finally, although jump speed was controlled for each individual approach speed was not, moreover participants moved as fast as possible but they had to control their jump-landings onto the force platforms, which does not replicate a real game situation. Future studies should measure males and females from different competition levels to get a better understanding of landing strategies. Moreover, it would be interesting to include different stimuli during the flight phase, to explore the effect of adjustments of the player's upper limbs which may vary the biomechanical parameters of the lower limbs during landing. For practical applications, coaches and trainers should plan training which considers the coordination in both directions and limbs, and performing preventative exercises unilaterally to minimize asymmetries. Furthermore, adapting training to simulate competition where players have unplanned situations could improve their performance which may reduce injury risk.

In conclusion, there were different strategies between limbs in all planes when participants performed a block jump-landing. It appears that the role of the limb, either lead or trail, is more important than the limb dominance when performing directional three-step block jump-landings. Our results suggest that the lead limb may have a greater risk of injury than the trail limb. Furthermore, when there was a planned situation, the athletes may have more conscious thought about their movement, or an internal focus, which might have changed their strategy, indicating greater implications to possible overuse injuries than in the unplanned situations which encourages an external focus.

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Annexes

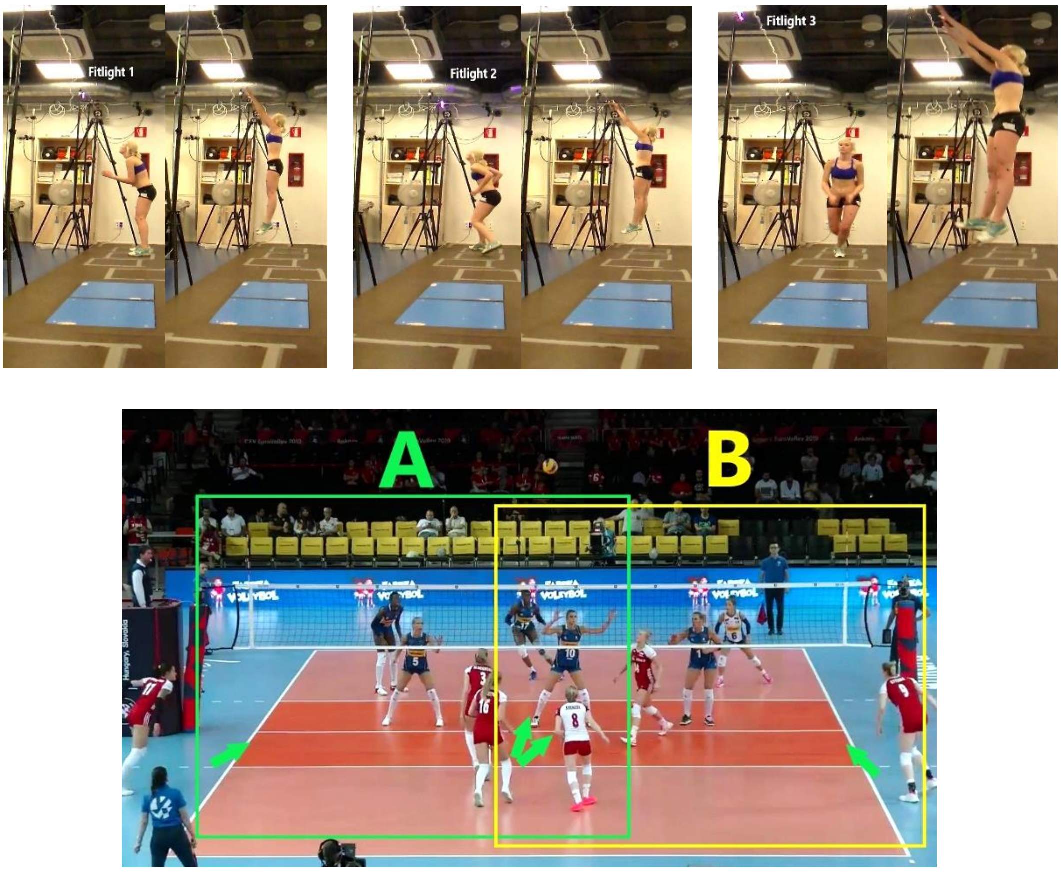

Figure 1. Up: example of a right-handed blocker in unplanned situation in front of three options of attack. Fitlight 1: frontal jump, Fitlight 2: short lateral jump, Fitlight 3: three-step block approach moving to the dominant direction. Down: example of a trial during competition in which the right-handed blue central blocker (in zone III) has all possibilities of attack. “Square A” represents the three attacks moving to their non-dominant direction and “Square B” represents the three attacks moving to the dominant direction. The two arrows inside both squares correspond with two possibilities of “first tempo attack” which likewise correspond with Fitlights 1 and 2. The lateral arrows of each square correspond with two possibilities of a “second tempo attack” which likewise correspond with the Fitlight 3, in “A” when moving to the non-dominant direction and in “B” when moving to the dominant direction

Table 1: Kinematic and kinetic variables for the Non-Dominant Limb joints during a block jump-landing in the sagittal plane (mean ± standard deviation)

	Planned		Unplanned				Anova *p* -value		
Hip	Non-Dominant Direction	Dominant Direction	Non-Dominant Direction	Dominant Direction	*p*-value P v UnP	Effect Size	*p* -value Direction	Effect Size	Interation
Peak hip flexion (deg)	56.6±12.9	54.32±14.25	60.13±11.44	54.09±11.81	0.227	0.119	**0.010***	0.434	0.105
Contact hip angle (deg)	20.97±3.67	22.27±5.75	23.95±4.38	22.17±4.05	0.098	0.211	0.784	0.007	0.106
Peak hip flexion moment (Nm/kg)	1.75±0.61	2.33±0.83	1.60±0.49	2.46±1.07	0.963	0.000	**0.009***	0.450	0.403
Peak hip stiffness (M/deg)	2.13±1.03	3.19±2.20	2.16±1.10	2.71±1.07	0.325	0.081	0.056	0.272	0.421
Peak hip power absorption (Mω)	1.75±1.43	3.45±2.54	1.31±0.96	2.73±2.62	0.125	0.185	**0.007***	0.466	0.764
Hip energy absorption (J/kg)	0.173±0.127	0.152±0.163	0.168±0.105	0.134±0.156	0.691	0.014	0.553	0.030	0.795
Peak hip flexion velocity (deg/s)	431.3±113.5	372.9±107.9	400.7±123.5	372.3±95.7	0.252	0.108	**0.015***	0.402	0.157
Knee									
Peak knee flexion (deg)	68.22±10.12	64.93±10.21	68.93±9.72	63.13±8.84	0.221	0.122	**0.022***	0.364	0.205
Contact knee angle (deg)	12.69±5.23	11.62±4.31	12.52±5.71	11.10±4.24	0.598	0.024	0.192	0.136	0.724
Peak knee flexion moment (Nm/kg) †	1.51±0.50	1.75±0.57	1.26±0.36	2.20±0.64	0.361	0.070	**0.011***	0.431	**0.000***
Peak knee stiffness (M/deg)	0.43±0.15	0.61±0.17	0.38±0.14	0.57±0.16	0.169	0.152	**0.001***	0.643	0.895
Peak knee power absorption (M.ω)	9.33±3.79	14.26±4.81	7.64±3.69	12.77±5.47	**0.005***	0.496	**0.003***	0.538	0.896
Knee energy absorption (J/kg)	0.763±0.384	1.177±0.528	0.583±0.326	1.134±0.541	**0.017***	0.391	**0.002***	0.564	0.275
Peak knee flexion velocity (deg/s)	588.68±51.94	604.52±76.70	587.53±52.16	590.10±69.4	0.517	0.036	0.527	0.034	0.560
Ankle									
Peak ankle dorsiflexion (deg)	23.51±4.42	23.70±3.25	22.52±5.13	23.75±4.69	0.357	0.71	0.298	0.090	0.235
Contact ankle angle (deg)	-34.60±6.29	-32.99±5.03	-35.89±6.79	-33.73±5.00	0.137	0.175	**0.036***	0.318	0.609
Peak ankle dorsiflexion moment (Nm/kg)	1.29±0.30	1.61±0.39	1.23±0.39	1.71±0.38	0.726	0.011	**0.010***	0.439	0.069
Peak ankle stiffness (M/deg)	0.06±0.01	0.10±0.03	0.07±0.02	0.10±0.03	0.531	0.034	**0.001***	0.593	0.943
Peak ankle power absorption (M.ω)	21.79±5.68	24.53±6.65	20.19±545	25.09±5.35	0.499	0.039	0.088	0.223	0.129
Ankle energy absorption (J/kg)	0.916±0.215	1.087±0.309	0.836±0.202	1.208±0.267	0.510	0.037	**0.006***	0.485	0.059
Peak ankle dorsiflexion velocity (deg/s)	1180.0±171.8	1147.9±155.1	1157.6±148.3	1151.1±157.	0.479	0.043	0.554	0.030	0.307

* Significance ($p \leq 0.05$). † Significant interaction between Non-Dominant - Dominant direction and Planned (P) – Unplanned (UnP). Deg – degrees; N – Newton; m- metre; kg – kilogram; M – Moment Joint; ω – angular velocity; J – Joule; s – second.

Table 2. Kinematic and kinetic variables for the Dominant knee during a block jump-landing in the sagittal plane (mean ± standard deviation)

	Planned		Unplanned		Anova *p* -value				
Hip	Non-Dominant Direction	Dominant Direction	Non-Dominant Direction	Dominant Direction	*p*-value P v UnP	Effect Size	*p* -value Direction	Effect Size	Interation
Peak hip flexion (deg)	51.31±12.85	60.01±12.86	54.18±13.42	59.04±11.35	0.370	0.067	**0.002***	0.561	0.075
Contact hip angle (deg) †	21.30±5.09	23.76±6.35	24.44±4.24	24.13±4.97	**0.028***	0.342	0.278	0.097	**0.048***
Peak hip flexion moment (Nm/kg)	2.04±1.07	1.26±0.37	1.83±0.60	1.24±0.37	0.412	0.057	**0.004***	0.510	0.527
Peak hip stiffness (Nm/deg)	2.51±1.00	2.38±1.99	2.52±0.81	2.48±2.32	0.789	0.006	0.869	0.002	0.819
Peak hip power absorption (Mω) †	2.74±2.38	1.75±1.20	1.54±1.33	3.88±3.65	0.352	0.072	0.170	0.151	**0.034***
Hip energy absorption (J/kg)	0.159±0.249	0.262±0.233	0.238±0.249	0.276±0.197	**0.033***	0.326	0.216	0.124	0.431
Peak hip flexion velocity (deg/s)	344.6±100.4	455.6±126.3	337.0±83.38	382.6±112.8	**0.026***	0.350	**0.001***	0.633	0.123
Knee									
Peak knee flexion (deg)	63.53±9.64	69.55±10.06	62.92±11.19	67.52±8.06	**0.024***	0.357	**0.002***	0.562	0.315
Contact knee angle (deg)	11.29±4.43	13.03±5.06	10.75±4.29	13.52±6.31	0.961	0.000	**0.014***	0.406	0.393
Peak knee flexion moment (Nm/kg)	2.21±0.44	1.29±0.42	1.96±0.38	1.22±0.39	**0.030***	0.334	**0.000***	0.662	0.132
Peak knee stiffness (M/deg)	0.52±0.24	0.36±0.10	0.48±0.11	0.37±0.10	0.577	0.027	**0.014***	0.408	0.543
Peak knee power absorption (M.ω)	11.54±5.81	7.16±1.51	10.37±3.51	6.85±2.32	0.125	0.184	**0.004***	0.512	0.431
Knee energy absorption (J/kg)	1.046±0.363	0.661±293	0.993±0.369	0.493±0.197	**0.041***	0.304	**0.000***	0.669	0.326
Peak knee flexion velocity (deg/s)	582.95±54.29	578.39±65.54	577.29±64.94	551.0±44.28	0.167	0.153	0.444	0.050	0.081
Ankle									
Peak ankle dorsiflexion (deg)	23.72±3.66	23.38±3.86	23.09±4.05	23.03±3.33	0.314	0.084	0.761	0.008	0.728
Contact ankle angle (deg)	-32.11±4.59	-34.03±4.53	-33.41±4.93	-34.15±5.01	0.266	0.102	0.087	0.224	0.269
Peak ankle dorsiflexion moment (Nm/kg)	1.74±0.32	1.34±0.43	1.85±0.27	1.40±0.48	0.157	0.160	**0.007***	0.469	0.676
Peak ankle stiffness (M/deg)	0.036±0.06	0.020±0.02	0.033±0.02	0.015±0.02	0.641	0.019	0.167	0.153	0.925
Peak ankle power absorption (M.ω)	25.09±5.21	21.71±6.76	25.65±4.34	24.07±7.90	0.967	0.000	**0.030***	0.335	0.481
Ankle energy absorption (J/kg)	1.157±0.246	0.900±0.282	1.239±0.256	0.891±0.308	0.445	0.049	**0.004***	0.521	0.366
Peak ankle dorsiflexion velocity (deg/s) †	1094.8±129.5	1183.3±135.3	1120.0±154.9	1127.1±144	0.357	0.071	0.070	0.248	**0.001***

* Significance ($p \leq 0.05$). † Significant interaction between Non-Dominant - Dominant direction and Planned (P) – Unplanned (UnP). Deg – degrees; N – Newton; m- metre; kg – kilogram; M – Moment Joint; ω – angular velocity; J – Joule; s – seconds

Table 3. Kinematic and kinetic variables for the Dominant and Non-Dominant knee during a block jump-landing in coronal and transverse planes (mean ± standard deviation)

Non-Dominant	Planned		Unplanned		Anova *p* -value				
Knee in the coronal plane	Non-Dominant Direction	Dominant Direction	Non-Dominant Direction	Dominant Direction	*p*-value P v UnP	Effect Size	*p* -value Direction	Effect Size	Interation
Peak knee valgus angle (deg) †	10.13±5.81	6.67±4.74	9.23±6.38	7.60±4.42	0.959	0.000	**0.002***	0.564	**0.007***
Contact knee angle (deg)	0.59±3.84	1.41±3.96	0.19±3.93	1.35±3.69	0.157	0.160	**0.003***	0.531	0.213
Peak knee valgus moment (Nm/kg)	0.03±0.10	0.26±0.26	0.04±0.13	0.24±0.19	0.777	0.007	**0.003***	0.535	0.614
Peak knee valgus angular velocity (deg/s)	121.6±58.3	103.3±44.3	117.5±60.1	101.3±39.8	0.702	0.013	0.156	0.160	0.912
Knee in the transverse plane									
Peak knee internal rotation tibial angle (deg) †	2.61±4.36	3.96±4.74	3.63±4.47	3.35±4.67	0.463	0.046	0.449	0.049	**0.017***
Contact knee angle (deg) †	1.43±4.23	3.37±4.91	2.52±4.59	2.68±4.76	0.564	0.028	0.101	0.208	**0.019***
Peak knee internal rotation tibial moment (Nm/kg)	0.01±0.05	0.08±0.06	0.01±0.04	0.08±0.06	0.495	0.040	**0.001***	0.624	0.879
Peak knee internal rotation tibial ang.vel (deg/s)	66.3±61.3	51.9±44.4	74.7±55.0	68.2±53.8	0.085	0.227	0.326	0.080	0.671
Dominant	Planned		Unplanned		Anova *p* -value				
Knee in the coronal plane	Non-Dominant Direction	Dominant Direction	Non-Dominant Direction	Dominant Direction	*p*-value P v UnP	Effect Size	*p* -value Direction	Effect Size	Interation
Peak knee valgus angle (deg)	6.31±3.76	8.92±4.00	6.75±3.91	8.29±5.04	0.674	0.015	**0.001***	0.582	0.076
Contact knee angle (deg)	1.83±3.18	1.46±2.94	2.00±3.29	1.37±2.63	0.833	0.004	0.050	0.282	0.445
Peak knee valgus moment (Nm/kg)	0.08±0.20	-0.06±0.14	0.12±0.19	0.01±0.17	0.091	0.220	**0.004***	0.521	0.735
Peak knee valgus angular velocity (deg/s)	83.4±51.0	82.2±47.0	72.4±47.5	69.8±54.9	0.275	0.98	0.798	0.006	0.950
Knee in the transverse plane									
Peak knee internal rotation tibial angle (deg)	3.93±4.34	3.38±3.44	3.27±4.67	3.30±3.61	0.287	0.094	0.691	0.014	0.416
Contact knee angle (deg)	3.33±4.76	0.96±3.31	2.77±5.00	1.38±4.75	0.879	0.002	**0.024***	0.356	0.311
Peak knee internal rotation tibial moment (Nm/kg)	-0.001±0.06	-0.017±0.04	0.013±0.06	-0.008±0.04	**0.028***	0.343	0.128	0.183	0.701
Peak knee internal rotation tibial ang.vel (deg/s) †	90.1±49.3	122.9±80.2	96.9±45.0	95.1±73.9	0.202	0.132	0.296	0.091	**0.024***

* Significance ($p \leq 0.05$). † Significant interaction between Non-Dominant - Dominant direction and Planned (P) – Unplanned (UnP). Deg – degrees; N – Newton; m-metre; kg – kilogram;; s – second.