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Original Article

Sex differences in kinetic and neuromuscular control during jumping and landing

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Abstract

In the present study, we analysed the kinetic profile together with the lower limb EMG activation pattern during a countermovement jump and its respective landing phase in males and females. Twenty subjects (10 males and 10 females) took part in the study. One experimental session was conducted in order to record kinetic and electromyographic (EMG) parameters during a countermovement jump (CMJ) and the subsequent landing phase. During the CMJ, males recorded a higher ($p<0.001$) performance than females in terms of jump height and power production. Stiffness values were lower in males than females due to greater centre of mass displacement during the countermovement ($p<0.01$). According to the EMG activity, males demonstrated greater ($p<0.05$) activation during the concentric phase of the jump. However, females revealed a higher co-contraction ratio in the plantar flexors during the push-off phase. During landings males showed higher ($p<0.01$) peak ground reaction forces (F_{peak}), greater ($p<0.05$) stiffness and a higher maximal displacement of the CoM ($p<0.05$) than females. EMG analysis revealed greater EMG activity in the tibialis anterior ($p<0.05$) and rectus femoris ($p=0.05$) muscles in males. Higher plantar flexor co-activation during landing has also been found in males. Our findings demonstrated different neuromuscular control in males and females during jumping and landing.

Keywords: Vertical jump, electromyography, force plate, ACL injury risk, stiffness

Introduction

The vertical jump is very important in sports and a high vertical jump contributes to successful athletic performance, particularly in sports such as basketball, volleyball, and football[1]. Vertical jump performance is influenced by mechanical and neural factors. It has been previously shown that the amount of elastic energy stored in the tendons by the prestretch loads positively influences jump performance[2]. An excessive rate of lengthening of the knee extensors during this phase can compromise their subsequent mechanical output by causing muscle to elongate too far from its optimum length according to the length/force relationship[3]. Related to the observations mentioned above, it has been found that females produce less power and jump height compared to male counterparts due to differences in force application[4] and muscle architecture[5].

The act of jumping and landing during different sporting activities also involves different magnitudes of ground reaction forces (GRF)6. The GRF magnitudes have been reported to be greatest during the landing phase of a jump when the knee is between 0° and 25° of flexion, a point at which it must resist a rapid change in kinetic energy[7]. Excessive GRFs may result in lower extremity injuries[8,9]. The knee is largely responsible for energy attenuation of the lower extremity when landing from a jump[10], so this joint may be more susceptible to injury during such a task.

It has been reported that ACL injuries are between two and eight times more likely to occur in women than in men participating in the same sport[11-13]. Moreover, up to 78% of these injuries occur in non-contact situations, such as when an athlete quickly decelerates or lands from a jump[14,15]. Specifically, prospective data have shown that the GRF during a jump-

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Table 1. Subjects' description (mean±SD).

	FEMALE	MALE	p value	d
Age (yrs.)	19.9±2.4	21.8±5.3	0.150	0.5
Height (cm)	165.7±9.2	176.5±3.3	0.001	1.6
Body weight (kg)	56.9±9.7	71.3±6.2	0.000	1.8
BMI (kg/m²)	20.5±2.2	22.8±1.8	0.008	1.1
BMI: body mass index. d: Cohen's effect size.				

landing task was 20% higher in female athletes who sustained an ACL rupture than in athletes who did not[16]. These data spark a compelling but unsubstantiated theory that reducing high GRFs may coincide with a decreased risk of knee injury. A positive moderate correlation between increased vertical GRF and increased anterior tibial acceleration when landing from a jump supports the hypothesis that individuals landing with greater impact loads could have an increased risk of ACL injury[17]. A biomechanical study revealed the ultimate load of ACL to failure could be as high as three times the body weight[18]. Video analysis reported that ACL rupture occurs within the first 100 ms after foot contact[19], indicating very high and rapid force values acting on the knee joint during an ACL injury.

It has been also reported that 'stiff' landings, characterised by lower knee and hip flexion, also produced higher ACL force than "soft" landings within a musculoskeletal model[20]. It could be that women are generally weaker overall in the lower extremity and thus need to use more muscle groups, or use muscle groups differently, to achieve neuromuscular control. In particular, possible sex-based differences in activation patterns may be necessary for women to generate the internal forces required to absorb landings from their maximal jump heights[21-23].

Most non-contact ACL injuries are reported to arise from a sudden deceleration while either running and changing direction or landing from a jump[24]. Some *in vivo* landing studies have provided considerable insight into joint kinematics[10], kinetics[10,25], muscle activation patterns[26], landing style[10] and energy absorption strategies[10,25] used during the landing motion. However, to our knowledge, sex-based differences in kinetics and neuromuscular control during the landing phase of a plyometric activity such as the countermovement jump (CMJ) have not been studied in depth. Furthermore, most ACL injury risk studies were performed using landings from a box[3,27], which seem a rather unrealistic approach to those happening during competition where landings from a jump are much more natural. In this regard, Abián et al[28] found substantial differences between male and females in the landing kinetics from a jump, so it is clear that sex-based differences in jumping and landing mechanics do exist. Therefore, in the present study, we analysed the kinetic profile together with the lower limb EMG activation pattern during a countermovement jump and its respective landing phase to better understand the possible mechanisms associated with the higher rates of ACL injury found in females.

Material and methods

Subjects

Twenty (10 males and 10 females) recreationally active participants (Table 1) from the Faculty of Sport Sciences of Toledo (Spain) were recruited. They routinely play different individual (e.g.: athletics) and team (e.g.: soccer, basketball, volleyball, handball...) sports at least twice a week. However, none of them was involved in systematic sports training. All the participants signed an informed consent prior to participation. Exclusion criteria for participation in the study were the occurrence of serious lower limb injuries as well as any health conditions precluding maximal strength and jump testing. The experimental procedures conformed to the Declaration of Helsinki and were approved by the local ethics committee.

Procedures

One experimental session was conducted. After the warm-up period, electrodes were placed on the right leg. Then, all participants started with a standardised warm-up protocol including 5 minutes on an ergometer and a dynamic warm-up for each of the major muscle groups to be used in the test exercises to ensure that the subject performed vertical jumps with maximal effort and without risk of injury. At the end of the warm-up, each subject performed two maximal CMJs on the force plate, with an inter-trial interval of 1 minute. The highest jump was used for further analysis.

Countermovement jump

The subjects were instructed to start in an upright position, rapidly squat, and then jump into the air with maximal effort. All participants wore their regular shoes. The hands were akimbo throughout the test in order to eliminate the effect of arm swing during the performance of each jump, and all participants received the same instructions: *'jump as high as possible and just land the way you want'*. During the squat phase of the jump subjects were required to bend their knees to approximately 90°, however, this was a mere reference, not a selection criterion. The test was performed on a Quattro Jump force plate (Kistler Instrument, AG, Winterthur, Switzerland). Ground reaction forces (GRF) were recorded at a sampling frequency of 500 Hz. All data were collected on a PC for further processing and analysis.

Electromyographic recordings

Electromyographic activity was recorded from the gastrocnemius medialis (GM), tibialis anterior (TA), vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF) in the right leg, using pre-gelled bipolar surface Ag-AgCl electrodes (Blue Sensor, Ambu. Inc.). Electrodes were placed over the muscle belly along the longitudinal axis of the muscle fibres, with ±2 cm inter-electrode distance, placing the reference electrode on the head of the fibula. Cables were secured with an adhesive tape and elastic mesh to prevent possible artefacts caused by movement. Electrodes were placed according to SENIAM guidelines[29]. The electrodes were connected to an eight-channel wireless data acquisition system (Noraxon Telemyo 2400T USA). EMG activity was recorded at a 1500 Hz sampling rate. All signals were amplified and filtered with a bandwidth from 10-500 Hz, where each channel has an input impedance >100 MOhm, common mode rejection ratio >100 dB and a gain=1000. All data were stored on a PC using Myoresearch XP v 1.06 software (Noraxon Inc. USA) for off-line processing and analysis. GRF and EMG signals were synchronised using an external trigger input.

Data analysis

Vertical acceleration (from the GRF) was evaluated in order to obtain the vertical velocity and displacement of the centre of mass[30], using the double integration method[31]. The height of the jump was obtained from the velocity value at the moment of take-off using the following equation: $H=v^2/2g$; where v is the take-off velocity and g the gravitational acceleration. Leg stiffness (K_{leg}) was defined as the ratio between force and CoM displacement (ΔL). K_{leg} was taken during jumping and landing when the force-time curve reaches the maximum value ($F_{peak}/\Delta L$)[32].

The EMG signals were band-pass filtered (10-500 Hz), and then full wave rectified. The root mean square (RMS) was calculated for the eccentric and concentric phase of the countermovement jump, and for the pre-activation (100 ms before initial contact) and landing phases (from the initial contact to the maximum displacement of the CoM after jumping). In order to normalise the EMG for better comparison between males and females, we used the RMS value recorded during the performance of maximum voluntary contractions (MVCs) of each isolated muscle before the testing protocol. Then, the data extracted from each muscle served as the reference (100%) to normalise the EMG during each analysed phase of the jumping and landing.

Muscle co-activation is the simultaneous activity of agonist and antagonist muscles acting around a joint[33]. The following equation was used to calculate the co-activation level during the different phases of the movement of the muscle antagonistic pairs at the knee and ankle joints (TA-GM, BF-VL and BF-RF): Co-activation= EMG antagonist / EMG agonist[33].

Statistical analyses

Descriptive parameters are shown as mean ± SD during the text and tables and as mean ± SE in the figures. Normal distribution of parameters was tested using Kolmogorov-Smirnov (Lilliefors) test. All data were normally distributed. In order to test differences between groups (males and females) independent t-tests were performed. Statistical significance was set at $P \leq 0.05$. SPSS 20.0 software (SPSS, Chicago, IL, USA) was used for statistical analysis. Cohen's "d" was also computed as a representative value of the effect size (ES). Threshold values for Cohen's ES statistics[34] were: 0.2 (small), 0.5 (medium), 0.8 (large) and 1.2 (very large).

Results

Regarding the countermovement jump (Table 2), analysis showed that males recorded a higher performance than females in terms of jump height ($p<0.001$; d=2.61), normalised jump height ($p<0.001$; d=2.16) and power production ($p<0.001$; d=1.78). Statistics also revealed lower K_{leg} values ($p<0.01$; d=1.35) in males than females. This lesser jumping stiffness revealed by male subjects is due to a statistically higher ($p<0.01$; d=1.57) CoM displacement during the downward movement of the jump, since no differences were found in F_{peak}.

During landings (Table 2), no differences were found between males and females in the time to reach the F_{peak} or in the CoM displacement at the time of F_{peak}. However, males showed a higher F_{peak} ($p<0.01$; d=1.22). This fact leads to greater landing stiffness ($p<0.05$; d=0.75) in males than in females. However, the maximal vertical excursion of the CoM was higher ($p<0.01$; d=1.06) in males than in females.

Figure 1 represents the normalised EMG values (%MVC) during the eccentric and concentric phases of the countermovement jump (left panel) and during the pre-activation and landing phases (right panel). It can be observed how males demonstrated statistically higher ($p<0.05$; d=0.62) RF EMG activation than females only in the concentric phase. However, during the landing phase the analysis revealed statistically higher EMG values in the TA ($p<0.05$; d=1.01) and RF ($p=0.05$; d=0.92) muscles in males compared to females.

Table 3 shows the co-activation ratio of different antagonistic muscle pairs around the knee and ankle joints. The analysis revealed that in the ankle joint, females showed higher ($p<0.05$; d=0.76) co-activation levels during the concentric phase of the countermovement jump, and lower co-activation ratios during the landing phase ($p<0.05$; d=1.58). During the landing phase females showed higher knee co-activation ratios than males, however these differences did not reach statistical significance ($p=0.15$; d=0.43).

Table 2. Kinetic parameters (mean ± SD) during jumping and landing (mean±SD).

JUMP	FEMALE	MALE	p value	d
F_{peak} (BW)	2.35±0.17	2.37±0.14	0.381	0.1
Jump height (cm)	26.49±3.27	36.75±4.49	0.000	2.6
Relative jump height (cm/BH)	0.16±0.02	0.21±0.02	0.000	2.2
Max power (W/kg)	43.36±2.58	52.91±7.13	0.000	1.8
ΔL (cm)	24.87±3.66	33.06±6.43	0.001	1.6
Jumping stiffness (BW/m)	5.28±0.84	4.02±1.02	0.002	1.3
LANDING	**FEMALE**	**MALE**	**p value**	**d**
Time to F_{peak} (s)	0.06±0.02	0.05±0.01	0.079	0.6
F_{peak} (BW)	4.60±1.02	6.04±1.33	0.005	1.2
ΔL at F_{peak} (m)	13.72±1.70	13.74±3.49	0.492	0.0
Máximum *ΔL* (m)	19.51±5.51	27.13±8.57	0.011	1.1
Landing stiffness (BW/m)	33.77±7.32	50.47±30.51	0.046	0.8

BW: body weight; ΔL: vertical displacement of the centre of mass. BH: body height; d: Cohen's effect size

Discussion

The current study shows that during the countermovement jumps carried out, significant differences were found between males and females in kinetics and neuromuscular control. The analysis revealed that males recorded a higher performance than their female counterparts in terms of jump height and power production (Table 2) which is consistent with previous studies[4,28]. These findings could be related to the theory that women are generally weaker overall in the lower extremity[35] due to differences in muscle thickness and relative fascicle length[5] that lead to a different force-time application during the performance of the jump[4]. Laffaye et al[4] reported a lower rate of force development during the eccentric phase of the CMJ, which could be directly related to less storage of elastic energy during the countermovement and decreased energy restoration during the push-off phase. This is also in accordance with the present results that show lower ΔL displacement during the downward movement when females are required to perform the CMJ, which in turn leads to greater stiffness values compared with males (see Table 2). In this regard, Voigt et al.[2] reported that the pre-stretching phase of the CMJ influences subsequent performance (jump height). This aspect may compromise subsequent mechanical output during the concentric phase by making the knee extensor muscle extend too far from its optimum length according to the length/force relationship[3].

Vertical jump performance is also dependent on neural factors. Our findings revealed that, during the concentric phase, males demonstrated higher EMG activity than females in the rectus femoris muscle (Figure 1). These data suggest that the number of motor units activated per unit of time was fewer in female subjects, an aspect that affects the ability of the neuromuscular system to develop high force levels as quickly as possible by the knee extensor muscles during the CMJ performance. This strong activation of the RF can also prevent excessive sliding of myofilaments, while at the same time allowing for a better combination of passive and active force/length curves during the following shortening of the knee extensors[3]. Furthermore, higher co-activation levels have been found in females compared to their male counterparts, during the concentric phase of the jump. Higher co-activation ratios have been previously linked to increased lower limb stiffness[10,32,33]. Lesser elasticity (or greater stiffness) of the muscle-tendon complex at the ankle joint, reduces the amount of mechanical work developed during the plantar flexion that occurs in the final phase of the vertical jump[36]. The fact that the ankle behaves less efficiently due to increased stiffness, could result in lower angular velocity and a lower mechanical moment during the concentric phase, which would compromise the final performance[32].

Some interesting sex-based findings were also observed during the landing phase. During landings, males showed higher landing stiffness than females. This higher K_{leg} could be explained by the greater peak GRF reached by males during the landing phase. Several studies have suggested that a stiffer musculoskeletal system is more advantageous than a compliant one when acute strain is applied to the lower extremity, so that stiffer muscles are better able to counteract deleterious forces and shield the ligaments from bearing the full responsibility of joint stability[37-39]. In this line of thought, it has been reported that female sex hormones have an influence on musculotendinous stiffness (MTS)[40]. MTS is reduced at week 3 of the menstrual cycle (ovulatory phase), leading to a greater reliance on the reflexive response from the contractile components of the muscle due to a decreased contribution from passive elastic structures and will also increase electromechanical delay[40]. Given that extreme loads are applied to the knee joint within milliseconds, the contractile components cannot respond quickly enough to counteract

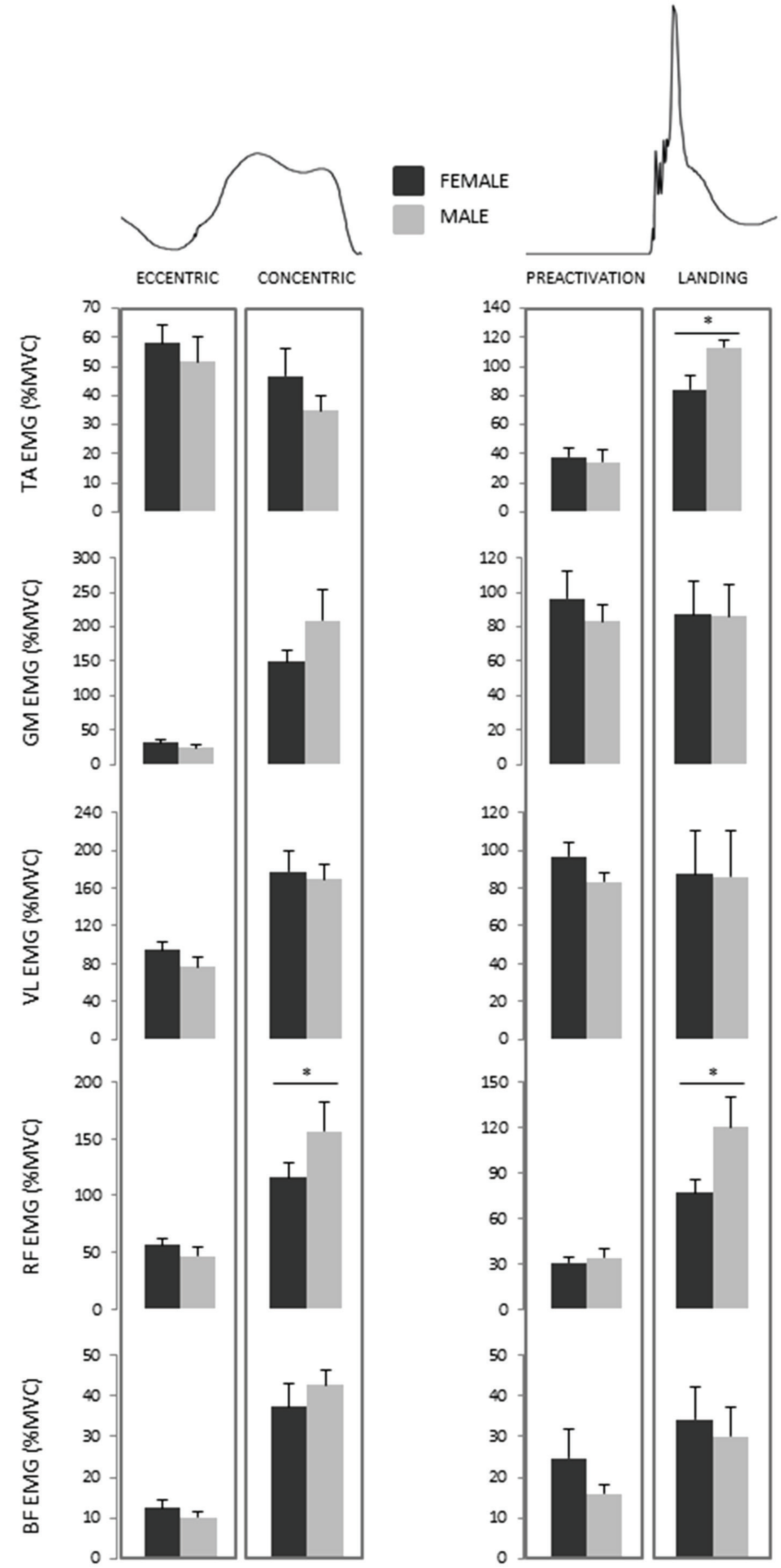

Figure 1. Normalised EMG values (%MVC) of the tibialis anterior (TA) gastrocnemius medialis (GM), vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF) muscles during the countermovement jump (left panel) and its landing (right panel) performed by females (dark grey bars) and males (light grey bars). * Significant differences between females and males.

Table 3. Co-activation ratios (mean ± SD) around knee and ankle joints during different phases of the jumping and landing movements.

	ANKLE CO-ACTIVATION (TA/GM)			
	FEMALE	MALE	p value	d
Eccentric	0.61±0.36	0.63±0.43	0.450	0.0
Concentric	0.36±0.31	0.20±0.11	0.045	0.8
Pre-activation	0.52±0.16	0.83±0.18	0.303	1.8
Landing	1.09±0.37	1.73±0.44	0.050	1.6
	KNEE CO-ACTIVATION (BF/VL)			
	FEMALE	MALE	p value	d
Eccentric	0.14±0.09	0.16±0.08	0.317	0.2
Concentric	0.25±0.18	0.28±0.15	0.307	0.2
Pre-activation	0.51±0.45	0.47±0.37	0.410	0.1
Landing	0.25±0.22	0.19±0.18	0.239	0.3
	KNEE CO-ACTIVATION (BF/RF)			
	FEMALE	MALE	p value	d
Eccentric	0.24±0.12	0.30±0.21	0.194	0.4
Concentric	0.34±0.16	0.34±0.18	0.458	0.0
Pre-activation	1.12±1.16	0.85±0.82	0.296	0.3
Landing	0.48±0.34	0.34±0.31	0.157	0.4

d: Cohen's effect size.

these sudden and potentially damaging forces[40]. However, the present study did not take into account the menstrual cycle of the female participants, so the contribution of some hormonal factors to the sex-based differences observed in landing stiffness cannot be discussed here.

Another interesting finding of the present study is that males also showed greater CoM displacement during the whole landing phase indicating a softer landing technique than females to absorb the forces reached during the initial impact with the ground. This is in accordance with previous studies[25,41] showing lesser knee flexion during female landings compared to those performed by male counterparts. This lesser knee angle demonstrated by females has been previously linked to a more erect body posture on impact[25,41]. Our EMG data also agree with this hypothesis, since higher knee co-activation ratios during landings were found in females compared to males (F: 0.25±0.22% vs. M: 0.19±0.18% for the BF/RF ratio; F: 0.48±0.34% vs. M: 0.34±0.31% for the BF/VL ratio). This indicates greater stiffness in the knee joint, which leads to a more rigid and erect body position during their landing movement. These findings seem to agree with a previous study which reported that increased knee joint stiffness is likely to increase injury risk during landing[42]. During soft landings the hip and knee muscles absorbed more energy than in a stiff landing condition[10]. This is reflected in the present study, since males showed higher RF EMG activation than females. However, these results seem to be in contrast to another study[27] which reported greater rectus femoris EMG in women compared with men. This may be due to a different testing protocol. While during this previous study[3,27] participants dropped from a box to land on one leg, the present study investigated landing control from a previous jump. This task (i.e.: CMJ) is more natural and is present in many sports disciplines such as volleyball, soccer, and basketball.

An additional finding from the EMG activity of the selected muscles during the landing phase was that the analysis revealed higher plantar flexor co-activation in males than in females (Table 3). One possible explanation is that this higher ankle co-activation may lead to preventing and offsetting further perturbations during the landing phase. It has been shown that a crucial mechanism used by the central nervous system to prevent falls from an external perturbation is related to an increased active muscle stiffness in the ankle plantar flexors[43]. It could be argued that males need to increase plantar-flexor coactivity for stabilisation of the balance posture during the landing phase, due to the fall from more height after the performance of a better jump.

In conclusion, sex-based differences were observed in performance and neuromuscular control during both jumping and landing. Although further research is needed to elucidate the ultimate mechanisms responsible for the increased ACL injury risk in females, our findings seem to point to different neuromuscular control strategies adopted during the performance of the jump and its respective landing. To our knowledge, sex-based differences in kinetics and neuromuscular control during the landing phase of a plyometric activity such as the countermovement jump (CMJ) have not been studied in depth. This kind of task occurs in most sports activities, so it seems rational to test the neuromuscular control during a CMJ to better understand the risk factors associated with ACL injury. ACL injuries are a major concern in athletics at all levels of sports competition. An understanding of the factors related to higher rates of ACL injuries in women could aid in carrying out more effective injury screening and prevention, to reduce the incidence and/or severity of ACL sports-related injuries.

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