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EXECUTIVE SUMMARY OF THE THESIS

Biomechanical assessment of Functional Landing Tests for ACL injury: gender differences

TESI MAGISTRALE IN BIOMEDICAL ENGINEERING – INGEGNERIA BIOMEDICA

AUTHOR: FEDERICO ADRAGNA

ADVISOR: Prof.ssa MANUELA GALLI

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1. Introduction

1.1. Background

While sports participation is encouraged in a healthy lifestyle, physical activities such as team sports can lead to injuries. Up to 78% of total injuries happen via a non-contact mechanism [1], with anterior cruciate ligament (ACL) tears being particularly common: it is estimated that up to 250000 ACL injuries happen every year [2].
Most non-contact injuries happen in sports involving sudden decelerations, landings and pivoting maneuvers such as football, basketball and volleyball [3]. Riskiness of these movements is related to instantaneous loading of all the body weight on one or both limbs, and it increases in unanticipated situations. Moreover, females are believed to be two to eight times more likely to sustain ACL injuries than males, due to anatomical, hormonal and neuromuscular factors [3].
Despite improved knowledge on prevention programs based on “Functional Tests” (FTs), injury rates in sports are not declining, highlighting the necessity of further research on the topic [4].

1.2. ACL injuries

The primary function of the ACL is to stabilize the knee, limiting excessive anterior dislocation of the tibia. A healthy ACL can resist to uniaxial tensions of more than 2500 N [5], values commonly reached during unusual stress conditions, such as awkward landing and cutting maneuvers. It is recognized that sagittal plane biomechanics are the major mechanism of excessive ACL loading, with excessive knee valgus and rotation contributing as well [6].
The recovery after such injuries begins with a surgical procedure to reconstruct the ligament, followed by a long rehabilitation process. It can

take up to eight months for the wound to heal, and the risk of relapse and permanent damage remains high [7].

1.3. Functional Tests

Dangerous motion patterns involve decreased flexion of the hip, knee and trunk, combined with excessive knee valgus and intra-extra rotation of the leg [8]. Researchers have tried to design a series of FTs to evaluate knee performance in a controlled environment. These specific FTs often involve squats, changes of direction (CoD) and landings. The latter seem to be the most employed in knee performance evaluation.
Landing tasks can be executed with one or two limbs, but single-leg tasks are considered more representative of real injury situations. They involve higher impact loads and knee valgus, combined with less knee flexion than double-leg tasks. Common landing FTs are the drop landing (DL), in which the subject steps off from an elevated position and lands, and the drop jump (DJ, *Figure 1*), which is a DL followed by a subsequent vertical jump (VJ).

Figure 1: Execution of a single-leg DJ.

There are other several variations of landing FTs, that may include: (1) a forward jump after landing, and its horizontal distance; (2) a VJ immediately after landing; (3) an immediate side cut (medial or lateral) after landing; (4) the starting drop height. These variations also interact with each other, this allows for great experimentation but limits the capability of comparing results. At present times no FT is considered the most effective to evaluate athletes' performance. [9].
Gender differences in sustaining ACL injuries have been the main topic of numerous studies, in which FTs highlighted women to have (1) increased tibial rotation [10]; (2) a more "stiff" landing technique, which involves low knee flexion at ground contact [11]; (3) an increase in knee valgus [12]; (4) greater coronal plane excursions for the hip, knee and ankle [13]. All these biomechanical factors are known to intensify the stress on the ACL.

1.4. Purpose of this study

The lack of standardized tasks has made it difficult to understand how FTs can be employed in clinical settings. An effort must be made to develop a series of FTs meant to improve current training programs, rehabilitation protocols and screening procedures.
The present study has two main purposes. The first one is to introduce a new series of FTs based on drop landings, with three main distinctions with respect to previous studies: (1) the use of an adjustable starting height of the box, depending on the height of the single athlete; (2) customized jump distance based on the maximum forward jump of every individual, meant to adjust the test difficulty according to the performance; (3) the combination of DJs with vertical or forward jumps and cutting movements, in lateral and medial direction. Secondly, this study aims to further proceed in the exploration of the gender differences showed in FTs, comparing the performances of female and male subjects when executing the proposed tasks.

2. Materials and Methods

Forty recreationally active athletes, 20 males and 20 females, were recruited for this observational study with a cross-sectional design. Subjects' age ranged from 18 to 25 years. Detailed information can be found in *Table 1*.

Gender	N	Age [years]	Height [cm]	Body Mass [kg]	Training sessions per week
Female	20	21.9 ± 2.2	170.0 ± 7.7	63.8 ± 8.7	3.6 ± 1.0
Male	20	22.0 ± 2.1	179.0 ± 5.6	73.9 ± 9.0	3.4 ± 0.9
Independent t-test (p-value)		0.883	< 0.001*	< 0.001*	0.628
Total	40	22.0 ± 2.1	174.5 ± 8.0	68.9 ± 10.1	3.5 ± 1.0

Table 1: *Anthropometric measures (mean ± SD) and subjects characteristics. Independent t-test was used to compare measures between groups. * denotes a significant difference, p < 0.05.*

The study was conducted in the Movement Analysis Laboratory of the University of Milan, equipped with a stereophotogrammetry system composed of 9 BTS-Smart E cameras (BTS S.p.A, Milan, Italy), with sampling frequency of 60 Hz. The system allows the 3D reconstruction of the position of every marker that moves in the predefined *acquisition volume*. In this study, a marker set composed of 38 reflective markers was employed, of which 26 were positioned directly on the athlete's skin and 12 were organized in four T-shaped clusters of three markers each. The spatial and temporal information of markers' trajectories is then processed to define the kinematics of the musculoskeletal system of the subjects.

2.1. Study protocol

In order to investigate lower limbs biomechanics, subjects performed 4 variations of single-leg DJs with the dominant limb, including: (1) customized height of the DJ starting point equal to 20% of subject's height; (2) forward jump distance equal to 60% of maximum single-leg horizontal forward jump distance; (3) the combination of a drop and a sequential jump in four directions. Executed tasks were:

- Drop Jump (DJ), which is a DL immediately followed by a maximal vertical jump.
- Drop Jump Lateral (DJL), that involves a DL and, immediately after landing, a maximal jump 45 degrees in the lateral direction with respect to the dominant limb.
- Drop Jump Medial (DJM), similar to the pervious task, but with the second jump performed 45 degrees in the medial direction.
- Drop Jump Central (DJC), that is a DL immediately followed by a maximal forward jump.

The study protocol required the acquisition of three valid trials per landing task type.

2.2. Data Elaboration

Data obtained from the trials were processed using the software SmartTracker (BTS S.p.A, Milan, Italy), to reconstruct the tridimensional trajectory of every marker during the tests (*tracking phase*).
Then, the files were further elaborated using the 3D biomechanics software Visual3D (C-Motion, Inc. Germantown, MD, USA), to extrapolate kinematic data such as (1) hip and knee angles in all three planes at ground contact and (2) hip and knee peak angles in a time window of 100 ms after ground contact, which is recognized as one of the time frames when most ACL injuries occur. In order to achieve better data quality, an interpolation with a third-degree polynomial was performed, followed by a low pass Butterworth filter with a cutoff frequency of 6 Hz.
The average values of the evaluated kinematic variables extracted from the three valid trials were calculated for each participant and used for the statistical analysis. All data were normally distributed.
Each kinematic variable was evaluated with the Two-Way ANOVA, in which factors were gender (male and female) and landing test (DJ, DJC, DJL, DJM). The significance level was set to $\alpha = 0.05$. If results were significant ($p < 0.05$) pairwise post-hoc comparisons, with Bonferroni corrections, were used to determine differences in the measured kinematic parameters between tests.
The effect size was evaluated using partial eta squared. The experimental effect was considered small for $\eta^2 = 0.01–0.06$, medium for $\eta^2 = 0.06–0.14$, and large for $\eta^2 > 0.14$. Finally, the post-hoc observed power was computed to evaluate the appropriateness of the chosen sample size.

3. Results

Results of kinematic variables and statistical analysis for between-gender comparisons are reported in *Table 2*. It contains results relative to the athletes' dominant limb kinematics at point of initial contact with the ground (IC) and the peak values in the following 100 ms.
At IC, significant differences ($p < 0.05$) were found for hip flexion (HF IC), knee abduction (KAb IC) and knee internal rotation (KR IC) angles. Women showed significantly less hip flexion (mean difference of 2.6°, $p = 0.015$) when compared to males, with small effect size (partial $\eta^2 = 0.038$).
Male athletes landed with an adducted knee, while women landed with a slightly abducted (valgus) knee (mean difference of 2.1°, $p < 0.001$), with medium effect size (partial $\eta^2 = 0.109$). Moreover, female athletes exhibited less knee external rotation when compared to male counterparts (mean difference of 2.1°, $p = 0.002$), with medium effect size (partial $\eta^2 = 0.063$). Results regarding hip adduction (HA IC), hip internal rotation (HR IC) and knee flexion (KF IC) did not highlight

significant differences between male and female participants, with p-values respectively 0.983, 0.233, 0.995.

Peak values in the 100 ms following the IC had significant differences for hip adduction (HA P), hip flexion (HF P), knee abduction (KAb P) and knee flexion (KF P). Women landed with an adducted hip, while men landed with the hip in abducted configuration (mean difference of 2.3°, $p = 0.005$), with small effect size (partial $\eta^2 = 0.050$). Female athletes had, again, significantly less hip flexion than males (mean difference of 5.4°, $p < 0.001$), with medium effect size (partial $\eta^2 = 0.091$). When compared to male counterparts, females exhibited increased knee abduction (mean difference of 2.6°, $p < 0.001$) with medium size effect (partial $\eta^2 = 0.135$). Furthermore, men showed greater knee flexion than women (mean difference of 2.7°, $p < 0.001$), with medium size effect (partial $\eta^2 = 0.092$). Results regarding HR P and KR P were not significant (p-values respectively 0.998 and 0.141), thus there were no differences between males and females.

Joint Angles [°]		Females	Males	p-value	Partial η²
Initial contact					
	HA	-13.0 ± 4.7	-13.0 ± 4.5	0.983	0.000
	HR	-6.3 ± 8.6	-7.9 ± 8.2	0.233	0.009
	HF	37.2 ± 6.0	39.8 ± 7.4	0.015*	0.038
	KAb	0.6 ± 2.7	-1.5 ± 3.3	<0.001*	0.109
	KR	-0.9 ± 3.5	-3.0 ± 4.8	0.002*	0.063
	KF	17.5 ± 3.4	17.5 ± 3.7	0.995	0.000
Peak					
	HA	1.2 ± 5.5	-1.1 ± 5.8	0.005*	0.050
	HR	3.6 ± 7.3	3.6 ± 7.4	0.998	0.000
	HF	47.9 ± 7.5	53.3 ± 10.0	<0.001*	0.091
	KAb	1.7 ± 3.1	-0.9 ± 3.7	<0.001*	0.135
	KR	4.7 ± 4.1	3.6 ± 5.1	0.141	0.014
	KF	53.8 ± 4.3	56.5 ± 4.5	<0.001*	0.092

Table 2: *Kinematic (mean ± SD) and statistical results of the between-gender comparison for all tests. Significant values are marked with *.*

The influence of test types was significant only in HA P ($p < 0.001$, with a large effect size, partial $\eta^2 = 0.142$) and in KF P ($p = 0.020$, with a medium effect size, partial $\eta^2 = 0.063$). These results are reported in *Table 3*. The test type did not significantly influence the other variables ($p > 0.05$).

A *post-hoc* test, with Bonferroni type adjustment, was then executed to investigate the statistical significances among the four FTs with respect to the two mentioned variables. The analysis of HA P showed that the DJL induced the highest peak of adduction, while during the DJM the hip was more abducted than in other tests. In particular, during the execution of the DJL, peak hip adduction was significantly higher than in the DJ (mean difference of 3.1°, $p = 0.05$) and DJM (mean difference of 5.4°, $p < 0.001$). HA P during the DJM resulted significantly lower than in DJC (mean difference of 4.4°, $p = 0.002$).

The knee was less flexed performing the DJC with respect to the other tests: the difference was significant only between DJC and DJM (mean difference of 2.7°, $p = 0.034$), but differences – although not significant – were found also between DJC and DJL ($p = 0.052$).

The post-hoc observed power of significant results for gender and between-tests differences ranges from 0.76 to 0.99.

Variable	Test*	Angle [°]	Comparison between tests (p-value)			
			DJ	DJC	DJL	DJM
Peak Hip Adduction						
	DJ	-0.7 ± 5.2			0.050	
	DJC	1.4 ± 5.1				0.002
	DJL	2.4 ± 5.8	0.050			<0.001
	DJM	-3.0 ± 5.6		0.002	<0.001	
Peak Knee Flexion						
	DJ	55.4 ± 4.0				
	DJC	53.3 ± 4.9			0.052	0.034
	DJL	56.0 ± 4.6		0.052		
	DJM	56.0 ± 4.4		0.034		

Table 3: *Results of HA P and KF P post-hoc analysis for comparison between tests after Bonferroni's correction. *Significant in Two-Way ANOVA (p < 0.05).*

4. Discussion

The results of this study highlighted different dominant limb biomechanics when comparing results of males and females.

At IC, women exhibited significantly less hip flexion than men. This is believed to increase risk of ACL injury in athletes because an extended lower limb may lead to inefficient load dissipation through ligament structures [14]. In addition, female subjects showed a less externally rotated and a more abducted knee when compared to males. Both frontal and transversal plane kinematics are recognized as key factors in knee injuries: excessive knee valgus and leg rotation increase strains on ligamentous structure and may lead to joint damage [8].

The study protocol yielded significant results also when analyzing lower limb kinematics in the 100 ms following IC. Women exhibited significantly higher hip adduction than men, who were found to have an abducted hip instead. The excessive hip adduction is commonly recognized as a risk factor for ACL injury, as it may induce the knee to stay in a valgus position [15]. Female athletes showed again lower peak hip flexion than male counterparts. Furthermore, women were found to have a significantly more abducted knee, while men exhibited a varus knee. Female athletes are recognized to have increased knee valgus at landing, and this may enhance the risk of ACL injury [13]. Lastly, women did not exhibit significant differences in knee rotation at peak when compared to men but showed lower peak knee flexion during the first 100 ms of the landing phase. Altered sagittal plane knee kinematics are believed to be a major risk factor for ACL injuries in female athletes due to the increased loads on the ligamentous structures when the knee itself is in an extended position [3].

The comparison of results of different landing tasks highlighted significant differences only in HA P and KF P. In particular, the hip was more adducted during the execution of the DJC and DJL, while it was abducted in the DJ and DJM. This could be associated to the motion pattern of the single task: the DJM required a second jump in the medial direction that made necessary an increase in hip abduction; conversely, in the DJL the subject jumped in the lateral direction thus executing a movement that demands hip adduction. Knee flexion was the lowest in the DJC with respect to other tasks, although this difference is significant only when comparing the DJC with the DJM. Nevertheless, differences between DJC and DJL results are very close to the significance threshold. The execution of a DJC involved higher hip adduction and lower knee flexion than other tasks, thus it can be theorized that this particular task was the most demanding for the knee, due to the fact that it was executed in a particularly "stiff" manner. Women showed an even stiffer landing strategy when compared to men, highlighting once again one of the reasons of higher knee injury rates in female athletes.

In conclusion, the present study provided new elements that may be of assistance when evaluating lower limbs biomechanics to assess ACL injury risk in athletes. It is the first study in which subjects performed DJ tests with sequential jumps in four directions, starting from personalized heights and forward jump distances. Moreover, although different tasks elicited different results, male and female subjects consistently showed different biomechanical behaviors when executing the proposed tasks, with female athletes performing riskier – in terms of ACL injury – motion patterns.

This study produced relevant results, but it still had some inevitable limitations.

Firstly, only kinematic variables were investigated. The use of a force platform to study landing kinetics would have greatly enhanced the results of the study. Secondly, there are many ACL injury risk factors other than biomechanical ones but his study only focused on the latter. Finally, it should be stated that landing tasks executed in a safe and controlled environment (e.g., the laboratory) often cannot resemble real life playing situations. Future studies should focus on trying to overcome said limitations in order to help develop effective prevention and training programs with the final goal of reducing ACL injuries in athletes.

5. Conclusions

In order to further expand knowledge about landing functional tests, 20 males and 20 females were recruited to perform four variations of a drop jump task (drop landing followed by vertical, lateral, forward, and medial jumps) to highlight gender differences. In addition, the protocol involved customized height and length of the drop

landing, to adapt the difficulty to the athletes' physical characteristics and performance.
The assessment of the proposed Functional Tests highlighted significant differences in male and female lower limb kinematics, showing how women executed a "stiffer" landing, with adducted hip and abducted knee, which are considered primary ACL injury risk factors. Between-tests comparisons showed that the drop jump followed by the central jump induced a high hip adduction and the lowest knee flexion, this may imply higher stress on the knee during the execution.
Results of the presented work are in agreement with those found in previous literature. The elements introduced in this study, meant to propose a standardized version of tests employed in previous studies, played a crucial role in obtaining significant results. Nevertheless, further research is required to inquire whether these adjustments may be of assistance in developing valid standardized tests to be used by clinicians in injury prevention and recovery, and in designing new training programs for athletes.

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