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DEVELOPMENT OF METHODOLOGIES FOR MEASURING MOTOR AND COGNITIVE PERFORMANCE IN A CLINICAL AND SPORTS ENVIRONMENT

Scientific disciplinary sector
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“The aim of science is not to open the door to infinite wisdom,

but to set a limit to infinite error.”

Bertolt Brecht – *“Life of Galileo”*

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AIM OF THE WORK

This PhD thesis is focused on the objectification of the health status of a subject both considering physical and cognitive aspects, which today represent a fundamental element in the experimental biomechanics applied both in sports and clinical fields.

The evaluation of the functional abilities of a subject, especially if he/she is an athlete, is a practice that is spreading among the various operators in the sector, and it is the subject of continuous analyses, reviews and updates by the scientific community. As it is well known, the functional assessment of human movement consists of a test battery and observations that are combined to determine, in an objective way, the abilities of the subject. In order to develop new evaluation methodologies, various criteria must be respected during the application of the method, its development, measurement and data interpretation. First of all, the methodology must be safe and not harm the subject, the test results must be reliable, repeatable and valid, the method used must be practical as the "cost" of the procedure must be reasonable and congruous to the purpose and finally useful, as it represents the degree of satisfaction of the needs of the evaluator and the subject.

Therefore, the purpose of this thesis is to propose new protocols for the assessment of motor and cognitive skills in sports, also focusing on innovative indices for the prediction of anterior cruciate ligament injury, as well as the analysis of the reliability and repeatability of innovative technologies for clinical evaluation, especially considering baropodometry and rasterstereography for postural analyses.

The thesis is therefore structured following these three main lines of research. The first section presents innovative protocols for evaluating motor and cognitive skills on international level karate athletes; in particular, the first part proposes an innovative evaluation protocol to analyze the differences between the sports specialties of kumite and kata using an optoelectronic system and a wearable inertial sensor, whereas the second part analyzes the possible effects on the cognitive abilities induced by technical karate training using a system of intelligent photocells. The second section focuses on the research and analysis of innovative predictive indices of anterior cruciate ligament injury using a wearable inertial system, the first part focused on women's basketball at national youth level and the analysis of a case study and the application of a machine learning structure, whereas the second on a protocol for analyzing the stability of the leg of a group of amateur footballers through innovative predictive indices. Finally, the third section deals with the analysis of the reliability of two systems widely used in clinical routines for postural analyses; specifically, the first part analyzes the response of a baropodometric system to the different feet positioning on the platform; whereas the second part analyzes the reliability and sensitivity of a 3D scanning system of the spine in different upright conditions for postural abnormalities identification.

1. MOTOR AND COGNITIVE EVALUATION IN KARATE

Do the specialties of kata and kumite lead to different motor skill development? An analysis on international level karatekas

Introduction

One of the most popular Japanese martial arts in the world is karate with over 9 million athletes and millions of practitioners worldwide [1]. The popularity and scientific interest of karate grew up in the last decades when the World Karate Federation has been recognized by the International Olympic Committee and it will make its first appearance as an Olympic Sport at the 2020 Summer Games in Tokyo. The karate competition consists of a sequence of attacks and defenses using kicking and punching techniques at very high speed and power [2]. Karate has two main technical specialties that represent the two disciplines in international tournaments: kumite and kata [3]. The word kumite is generically translated as "combat"; As a result, karatekas use basic techniques to interact while competing against an opponent. In kumite fights a high intensity activity is required, involving kicks, punches and rapid horizontal movements for a duration of about 3 minutes [4]. It is easily understood that the main aspects that should be trained in kumite karateka are perceptive and anticipatory skills [5]. Conversely, kata competition can be considered as a virtual fight as it consists of a standardized sequence of offensive and defensive gestures against an imaginary opponent [6]. Both competitions are characterized by periods of less intensity and periods of maximum work [7]; therefore, maximum speed and explosive power are crucial elements of karate performance [8]. In the past, coaching programs were similar for both techniques and most athletes successfully participated in both kumite and kata during official competitions. However, the revised competition rules have made kumite more dynamic than kata; consequently, adequate specialization in elite karateka should be required according to the specific technique [9].

In recent years, technological innovations have facilitated the assessment of motor performance through the use of wearable sensors [10-14], even in combat sports [15-17]. To identify the best discipline between kata and kumite for each karateka, information regarding the physical and physiological characteristics of the athletes must be taken into consideration [18]. In particular, physical characteristics include speed, stability, power, mobility, coordination and agility while physiological aspects include cardiorespiratory endurance, muscle strength and body composition [19].

Studies on the physiological and physical differences between kata and kumite have already been conducted in recent years. These studies were mainly focused on the evaluation of metabolic consumption [20], stability [1, 21], agility [4, 22, 23], mobility and power [23].
Regarding metabolic consumption, Doria *et al.* found a greater demand for metabolic power in kumite practitioners than kata practitioners (on average 155.8 ml / kg versus 87.8 ml / kg), with the aerobic intake predominating [20]. Focusing on stability skills, Mirmoezzi *et al*. found that kumite athletes showed better dynamic balance, but this improvement diminished with fatigue caused by intense training [21]. Other work on stability is by Gauchard *et al*., They evaluated postural performance in high-level kumite and kata by comparing them with sedentary subjects

while performing static balance control under different visual and tactile conditions, i.e. eyes open/closed and on various tactile supports. As expected, more body oscillation emerged in sedentary subjects than in athletes when performing bipodalic tasks; furthermore, focusing on the two disciplines, kata athletes were characterized by a reduction in body oscillation in both visual and tactile conditions [1]. Specifically, the kata showed a reduction from 100 to 40 mm2 considering all conditions tested. The authors suggested that such results may be related to the different postural strategies required for karateka specialization and therefore suggested implementing training programs to delay the effects of fatigue, especially in kumite karateka.

Turning to the assessment of agility, Syaquro *et al*. found no differences in reaction time between the two disciplines during full-body rotation but found a difference in reaction speed (mean kumite = 0.32s and kata = 0.23s). In particular, kumite showed the best results attributable to the need for kumite to react quickly to the opponent's movements during the competition [22]. Nedeljkovic *et al*. evaluated the reaction time in offensive and defensive actions performed by kumite, kata and beginners. The authors found differences only between beginners and others; while a promising but not significant difference was observed between kumite and kata, with the former characterized by lower values of the reaction time [4]. Furthermore, the study conducted by Zemkova revealed that the agility index was significantly better in kumite athletes than in kata athletes (on average 270 ms vs 330 ms); the opposite result was obtained for movement speed [24]. Regarding mobility and power, only Koropanovski *et al*. aimed at identifying the differences due to the kumite and kata disciplines on anthropometric characteristics and physical performance [23]. The authors implemented a protocol that includes several tasks to evaluate lower limb agility, mobility, endurance and power discovering that explosive power could be fundamental in the kumite technique; while a smaller stature and greater mobility of the lower limbs could be relevant for kata athletes. The authors suggested how the reported results could be useful for a first selection of karate competitors.

To the best of the authors' knowledge, no studies have been conducted to investigate the differences due to karate techniques in elite athletes on jumping ability, single stance stability and upper limb mobility which is one of the basic fitness components in karate for performing full-range movements at high speed [18]. In addition, jumping and single-stance stability are movement tasks often required during competitions [25]. From this point of view, the objectives of the study were twofold. Firstly, we wanted to evaluate the differences in motor performance between elite karateka and non-karateka, aiming to create reference values of physical performance in elite karateka useful to direct beginners towards the most appropriate training programs. Secondly, we aimed to measure the influence of karate specialties on physical performance in elite athletes; in particular, we wanted to evaluate the differences between kata and kumite athletes in terms of full-body joint mobility, body stability and jumping ability. The results of the second objective could be useful to provide guidelines for the optimization of coaching programs based on the specific technique of karate.

Materials & Methods

Participants

Twenty-four international level karatekas (11 men and 13 women) with at least 15 years of practice and belonging the Italian national karate team were involved in the study. More specifically, 16 of them were kumite athletes (KU - seven males and nine females, age = 24 ± 6 years, height = 169.4 ± 7.6 cm, body mass = 64.8 ± 9.4 kg) and the remaining eight kata athletes (KA - four males and four females, age = 26 ± 5 years, height = 165.4 ± 5.6 cm, body mass = 66.8 ± 4.4 kg). Among them, there were winners of the Italian championship, European champions and World champions in different weight categories. All of them were involved in karate six days per week and twice for each day. In addition, 18 age-matched subjects (thirteen men and five women, age = 25 ± 6 years, height = 171.2 ± 8.6 cm, body mass = 69.8 ± 10.4 kg) were involved in the study as non-karatekas (NK). Subjects were included in the NK group if they did never practice karate and they practice physical activities at maximum twice per week, not at a competitive level. Participants, both karatekas and non-karatekas, had not any recent injuries for at least 2 years. All participants were informed on the rationale of the study and a written informed consent was obtained according to the ethical standards outlined in the 1964 Declaration of Helsinki.

Experimental Setup

Two sensor systems were used in the experimental protocol: the OPTOGait and the GyKo.
The OPTOGait system (OPTOGait, Microgate S.r.I, Italy, 2010) consists in a set of transmitting-receiving 1 m long bars positioned above the ground. Each bar is equipped with ninety-six LED diodes. Data were recorded using OPTOGait Version 1.12.1.0 software (Microgate S.r.I, Italy). Through this device it is possible to record flight and contact times of each foot with an accuracy of 1 ms. The sampling frequency was set at 1 kHz. The OPTOGait system is commonly used in the analysis of human movements, especially for gait [26], [27] and jump gesture analyses [28].

The GyKo inertial sensor system (Microgate S.r.I, Italy) contains the MPU9250 that is a single Magneto Inertial Measurement Unit - MIMU (dimensions: 50 × 70 × 20 mm, mass: 35 g) consisting in a triaxial accelerometer (full scale ranged from ±2g to ±16 g), a triaxial gyroscope (full scale ±2000 °/s) and a triaxial magnetometer (full scale ±4800 µT). The device can be fixed on a body segment using a dedicated semi-elastic belt equipped with a device-specific magnetic support to avoid relative movements during the execution of the tasks. Elastic belt guarantees also the subject comfort. Data gathered from the sensor is transferred via Bluetooth to a personal computer and stored using the GyKoRepower software v. 1.1.2.0 (Microgate S.r.I, Italy). The sampling frequency was set at 500 Hz. The MPU9250 is characterized by an accuracy of ±0.1 ° in the angle computation [29]. The GyKo inertial sensor is mainly used to evaluate motor activities in jump tests [30], muscle strength test [31] and stability tests [32]; and its measures have been demonstrated to be reliable in both angle [33] and postural parameters computation [34].

Finally, two Webcams (Logitech C920 HD) were set at 3 m from the subject and were aligned with her/his frontal and lateral planes. Video were synchronized with data acquisition in order to record movements of the subject during the entire protocol. Videos were successively analyzed to verify the correctness of the task execution in order to evaluate tasks to discard from the analyses.

Experimental Protocol

The experimental protocol consisted of three tasks for the evaluation of whole-body joint mobility, monopodalic stability and jumping ability. All the physical exercises were developed according to the requirements of the technicians of the Italian national karate team. All tests were carried out directly on the mat in barefoot condition. Before each task, a static acquisition with the sensorized body segment in rest position was performed. The rest position coincided with the starting position specific for each individual test, as described in the following paragraphs. All participants were able to complete the entire protocol that lasted approximatively 45 minutes per subject.

Joint Mobility

As regards joint mobility tasks, participants were asked to perform selected movements of shoulder, hip and ankle joints with the greatest possible excursion at the preferred velocity without making compensations with other parts of the body. In addition, only for the shoulder movements and hip flexion movement, participants were asked to move body segments also at the maximum velocity (MV). Each required movement was repeated once. Participants were instrumented with the GyKo placed on the body segment proximal to the examined joint in order to measure the linear acceleration and angular velocity of the segment, which the sensor was attached on. The full scale of the accelerometer embedded into the GyKo was set to ±2 g in mobility tasks. The OPTOGait sensor was not used in the mobility task.

Shoulder

For the analysis of shoulder mobility, four movements were performed: flexion, extension, abduction and extra rotation. As regards the first three movements, participants were asked to stand on the mat and to perform the requested rotations starting with the arms along the body (Figure 1); for the extra rotation, instead, subjects started with an abduction of shoulder equal to 90° resting the forearm and the hand on a flat support, as it is shown in Figure 2. During flexion and extension movements, subjects were requested to avoid intra and extra rotations, instead natural physiological movements were allowed during the abduction rotation. The device was placed on the subject's arm at 15 cm from the center of rotation of the shoulder during the flexion, extension and abduction movements (Figures 1.a and 1.b). For the extra-rotation movement, the sensor was placed on the forearm at 15 cm from the elbow (Figure 1.c) All the movements were performed with both sides and at both preferred and maximum velocity. Each movement was repeated once.

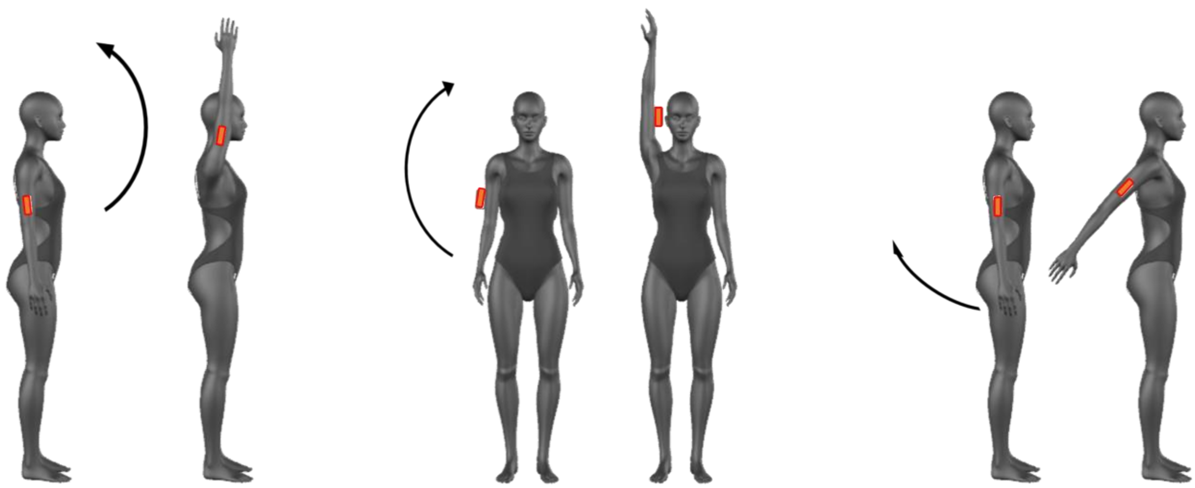


Figure 1. Mobility of shoulder: sensor positioning and movement direction for the flexion (a), abduction (b) and extension (c) task.

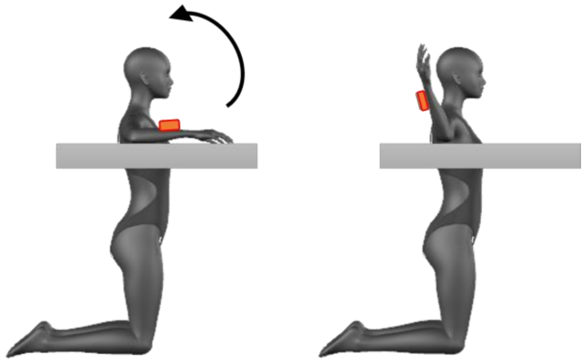


Figure 2. Mobility of shoulder: sensor positioning and movement direction for the extra-rotation task.

Hip

For the analysis of the hip mobility, three movements were performed. The first movement was a hip flexion starting from the supine position with the legs resting on the ground (Figure 3.a); subjects were asked to avoid knee bending. The second movement, denominated split movement, consisted in a hip abduction performed with the two limbs simultaneously, starting with legs resting on the wall and the trunk extended on the ground; the hip flexion was maintained at 90° during the rotation (Figure 3.b). Finally, the third movement, denominated sit and reach, consisted in a further hip flexion performed with the trunk and starting from the sitting position with the legs straight on the floor (Figure 3.c); the rotations simulated a reaching movement [35]. The sensor was placed on the thigh at 15 cm from the knee center of rotation during the flexion and split movements (Figures 3.a and 3.b). For the sit and reach movement, the sensor was placed on the back at level L-4 (Figure 3.c). The flexion movement was performed with both sides; the split movement was repeated two times in order to measure one movement per each leg. Only the flexion movement was performed at both preferred and maximum velocity.

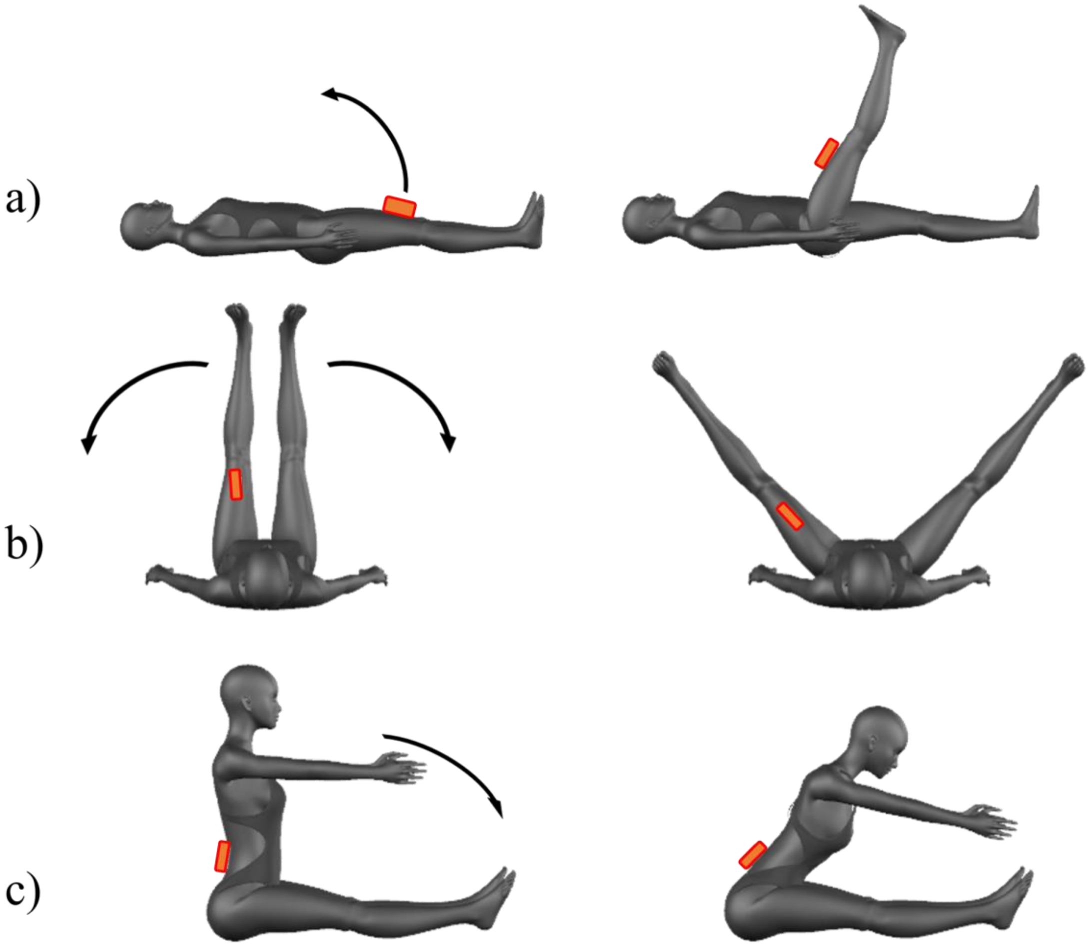


Figure 3. Mobility of hip: positioning of the sensor and movement direction for flexion (a), split (b), and sit and reach (c) task.

Ankle

For the analysis of the ankle mobility, two movements were performed. The first movement was an ankle flexion caused by the foot rotation starting from a fully extended position of foot with the subject lying prone on the couch and the feet outside of it (Figure 4.a). The second movement was an ankle flexion caused by the leg rotation during an overhead squat (Figure 4.b). The sensor was positioned on the plantar fascia of the foot (Figure 4.a) during the flexion task and on the shank at a distance of 10 cm below the knee during the squat movement (Figure 4.b). The flexion movement was performed with both sides; the squat movement was repeated two times in order to measure movement once per each leg. Ankle movements were performed only at the preferred velocity.

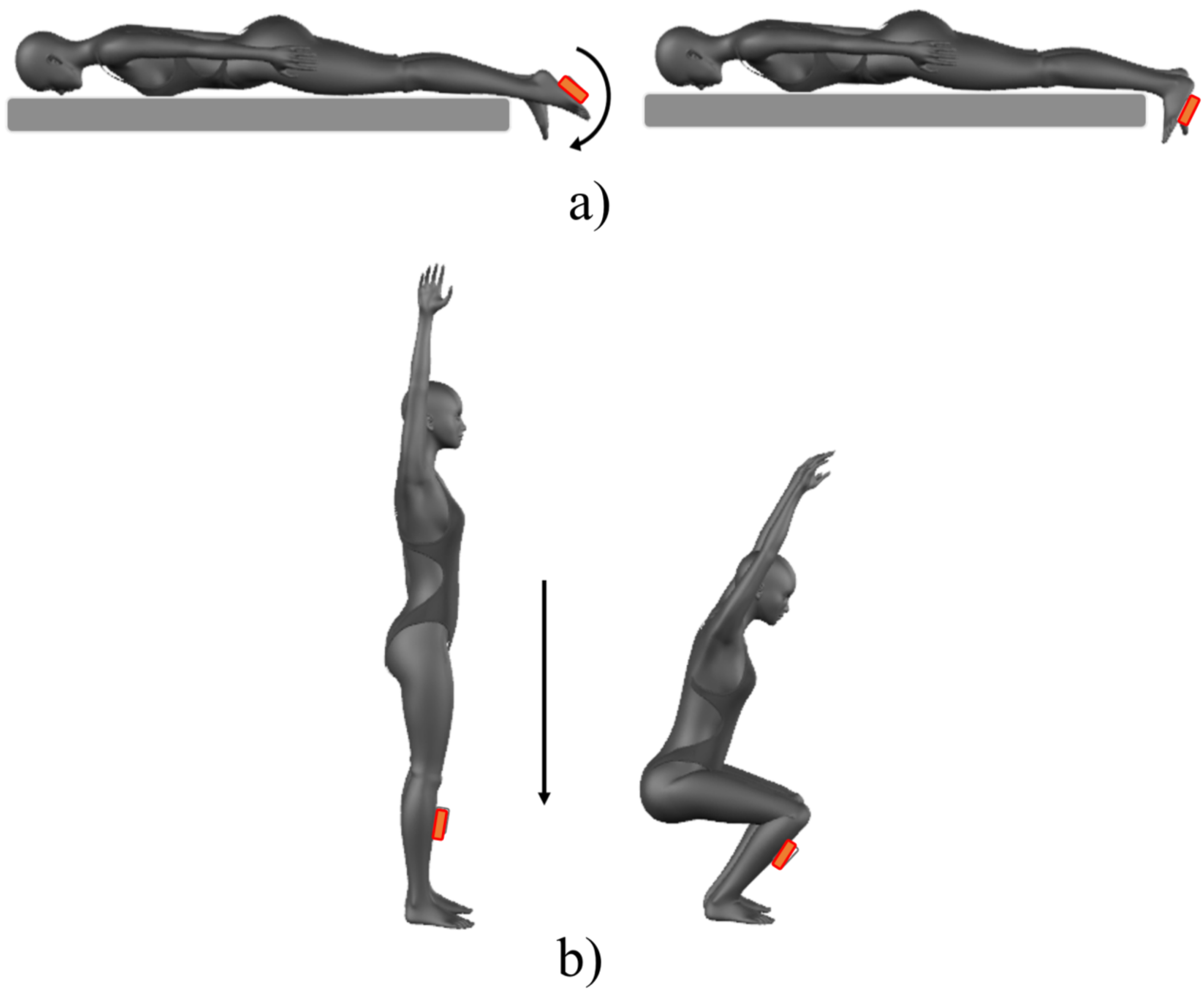


Figure 4. Mobility of ankle: positioning of the sensor and movement direction for flexion (a) and squat (b) task.

Body Stability

As concerns body stability, a novel monopodalic test was developed starting from the One-Leg Standing Balance [36], [37] and modifying the position of the arms and the raised leg in accordance with the indications provided by the karate technicians. More specifically, participants were asked to stand on one foot with hip, knee and ankle of the other leg flexed at 90 ° for 15 s maintaining the hands crossed behind the head.

Participants were instrumented with the GyKo placed on the back at level L4 in order to measure the linear acceleration and angular velocity of the pelvis, which the sensor was attached on (Figure 5). For each subject, the distance between the sensors and the ground was measured. The full scale of the accelerometer embedded into the GyKo was set to ±2 g in stability tasks. The OPTOGait sensor was not used in the balance task. The test was performed with the dominant leg [38] and with both open and closed eyes (EO and EC). During the EO condition, subjects were asked to fix a point on the wall at 5 m. The test was considered completed if the subject did not touch the ground with the raised limb or if he/she opened the eyes in EC condition within 15 s. Each condition was recorded once after an initial period to familiarize with the task.

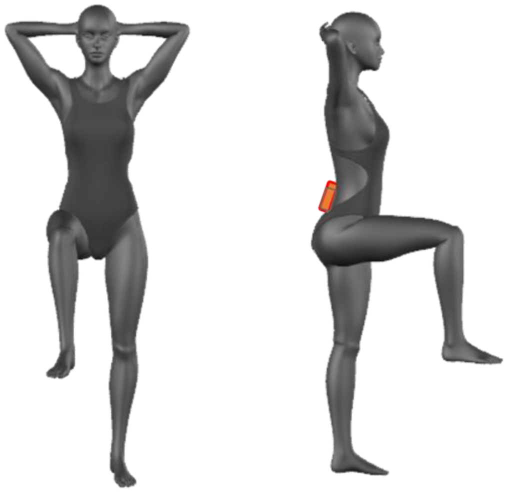


Figure 5. Balance test: positioning of the subject and sensor.

Jumping Ability

As regards the analysis of jumping motor performance, jump tests included Squat Jumps (SJ), Countermovement Jumps (CMJ) and Repeated Countermovement Jumps for 15 s (RCMJ) [23], [39]. In both jumps, the subjects were asked to start from a standing position with their feet shoulder-width apart and their hands on the iliac crests. In SJ, the athletes descended into a semi-squat position and held this position as long as they wanted before initiating the successive upward/concentric phase to jump. Conversely, in the CMJ the subjects performed a downward movement, which is immediately followed by the concentric phase without the maintaining of the semi-squat position [40]. All the jumps were carried out on the mat, without the help of the upper limbs, *i.e.* subject were instructed to maintain the hands attached to the body for the whole task. Participants took a 2-minute rest between each test to avoid fatigue effects [41], [42]. Participants were asked to jump as high as possible without any restrictions of the knee angle during the squat phase. SJ and CMJ were repeated two times, instead the RCMJ was performed only once. Participants were instrumented with the GyKo placed on the back at L4 level to collect the linear acceleration and angular velocity of the pelvis. The full scale of the accelerometer embedded into the GyKo was set to ±16 g in jumping tasks. The OPTOGait system was positioned on the tatami with bars at 2.5 m (Figure 6).

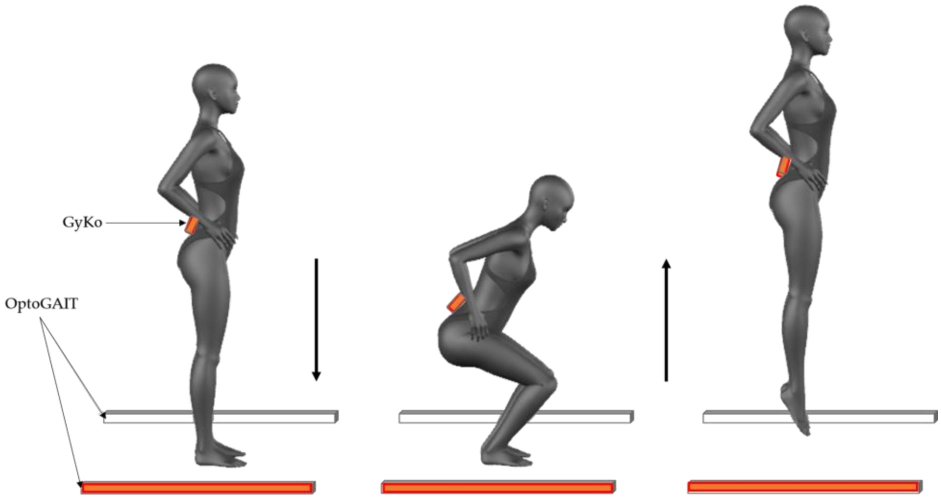


Figure 6. Jump test: subject and sensor position and sequence of movements

Data Analysis

Data gathered during static trial was used for the re-alignment of the sensor axes with the absolute reference system; successively linear accelerations and angular velocities gathered from the GyKo were processed using a Mahony filter to compute the orientation of the sensor [43]. This post-processing operation was conducted for all the performed tests. Videos recorded during the task execution were carefully checked to discard trials in the following cases: (i) incorrect movements during the mobility tests; (ii) inability to perform the monopodalic tests, i.e. touch the ground with contralateral leg or open the eyes during the EC condition; and, (iii) incorrect position and execution during jumping task. Only the second situation occurred, as reported in the paragraph 3.2.

Joint Mobility

As regard mobility tests performed at the preferred velocity, we defined as θ the highest difference between the angle computed during the execution of the movement and the one gathered at the start of the task with the body segment in the rest position, along the examined axis. Successively, $\dot{\theta}$ was defined as the average velocity of the performed movement.
By moving to the tests performed also at the maximum possible velocity (MV), i.e. all shoulder movements and the hip flexion, the same values were computed and they were addressed as θ_{MV} and $\dot{\theta}_{MV}$.

Body Stability

Body stability was analyzed considering the projection of the vertical axis of sensor on the horizontal plane corresponded to the floor. The point represented by this projection was evaluated knowing the distance between the position of GyKo sensor and the floor that was initially assessed by a measuring tape. The evaluated point can be assumed as the center of pressure (COP); then, the antero-posterior (AP) and the medio-lateral components (ML) of the COP were computed. Finally, as stability indices we computed parameters that are typical considered in posturographic analysis [44]–[46]. Specifically, the path length (PL), the ellipse area (EA) and the mean frequency (FREQ) were evaluated by following the equations reported in [45].

The path length (PL) was defined as the total length of the COP path computed by the sum of the distances between two consecutive points of the COP path (Equation 1).

$$PL = \sum_{n=0}^{N-1} [(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2]^{1/2} \quad (1)$$

where N represents the number of points of the COP. The PL was also evaluated considering the antero-posterior (PL_{AP}) and medio-lateral (PL_{ML}) components one at a time.

The 95% confidence ellipse area (EA) was computed representing the area of the 95% bivariate confidence ellipse, which was expected to enclose approximately 95% of the COP (Equation 2).

$$EA = 2\pi F_{.05[2,N-2]} [s_{AP}^2 s_{ML}^2 - s_{APML}^2]^{1/2} \quad (2)$$

where $F_{.05[2,N-2]}$ is the *F* statistic at a 95% confidence level for a bivariate distribution with *N* points. s_{AP}^2 and s_{ML}^2 are the variance of the AP and ML, and s_{APML}^2 is the covariance.

The mean frequency (FREQ) was defined as the angular frequency of the COP if it had traveled the total excursions around a circle with a radius equal to the mean distance (MD) and it was evaluated as (Equation 3):

$$FREQ = \frac{VEL}{2\pi MD} \quad (3)$$

where VEL was the average velocity of the COP and MD was the average distance of each COP point from the origin defined as the projection of the gravity vector on the floor (Equation 4):

$$MD = \frac{1}{N} \sum_{n=1}^{N-1} \sum [AP[n]^2 + ML[n]^2]^{1/2} \quad n = 1, \dots, N \quad (4)$$

and VEL was the average velocity of the COP. The FREQ parameter was also evaluated considering the antero-posterior ($FREQ_{AP}$) and medio-lateral ($FREQ_{ML}$) components individually.

The stability indices were calculated by eliminating the first 3 s of the test to discard the transition phase where the subject moved from the relaxed position, on two feet, to the monopodalic position.

For all the above-mentioned parameters, the Romberg Index (RI) was also computed as the ratio between the stability parameters obtained during the EC and EO conditions [44]. Values of RI close to 1 indicate a better adaptation to the closed eyes condition.

Jumping Ability

As concerning the jump tests, the time instants in which the subject hit and detached himself from the ground were estimated by using the OPTOGait system. The linear acceleration gathered from the GyKo was integrated to obtain the linear velocity in order to identify the eccentric and concentric phases of the jumps. Specifically, the eccentric phase is identified as the time interval between the start of downward movement and the instant of time in which the subject reverses the movement, *i.e.* the zero of the velocity, and starts pushing upwards. The concentric phase, instead, is defined as the time interval between the end of the eccentric phase and the instant in which the subject jumps from the ground. In the SJ the Flight Time (T_F) and the Concentric Phase Time (T_{CP}) were evaluated. In the CMJ, we also computed the Eccentric Phase Time (T_{EP}). For both SJ and CMJ, all indices were averaged across the two repetitions for each participant. All previous parameters were computed also during RCMJ and, in addition, we evaluated the Contact Time (T_C).

Statistical Analysis

Data computed for all the examined tasks was firstly tested for normality with the Shapiro Walking test.

As regard, the index computed for the mobility test, a one-way ANOVA test was performed considering the three groups as independent variables and by considering one index per time. Thus, a total of 28 ANOVA tests were performed considering each mobility index independently. Similar steps of statistical analysis were performed for each index related to the jumping test for a total of 9 ANOVA tests considering each jumping index independently. As regards the body stability task, one-way ANOVA test was performed considering the three examined groups as between-subject effect. It is worth highlighting that the results obtained for the two visual conditions were tested independently. Thus, a total of 21 ANOVA tests were performed considering each stability index independently.

For all the ANOVA tests, a Bonferroni Post-Hoc multiple comparison test was used to determine differences among means when ANOVA test was significant. Statistical significance was set at $p < 0.05$ for all the performed tests.

The statistical power analysis was performed through the G*Power software [47]. Power values ranged from 82% to 91% were found, considering a medium effect size (0.5) [48].

Results

Joint Mobility

Mean values and standard errors of the angles computed during the joint mobility tasks performed at the preferred velocity and the relative statistical results are reported in Table 1. Right and left values were considered together due to similar results between the two sides obtained in a preliminary analysis within each group.

Table 1 – Mean values (standard errors) for θ and $\dot{\theta}$ obtained during the joint mobility test performed at the preferred velocity for all the examined groups. KU, KA and NK stand for kumite, kata and non-karatekas group, respectively. Superscripts represent statistical differences, with * indicating difference among all groups.

		θ (°)			$\dot{\theta}$ (°/s)		
		KU	**KA**	**NK**	**KU**	**KA**	**NK**
Shoulder	Flexion	179.2 (2.1)^{NK}	172.0 (2.1)^{NK}	160.1 (1.8)^{KA,KU}	278.4 (24.6)^{NK,KA}	143.4 (23.2)^{KU}	199.1 (8.4)^{KU}
Shoulder	Extension	82.1 (2.3)^{NK,KA}	68.1 (2.8)^{KU}	66.3 (1.8)^{KU}	178.8 (20.3)^{NK,KA}	90.5 (19.1)^{KU}	105.0 (6.5)^{KU}
Shoulder	Abduction	172.6 (1.7)^{NK}	171.4 (2.3)^{NK}	155.0 (2.2)^{KA,KU}	306.1 (26.8)^{NK,KA}	148.7 (30.9)^{KU}	215.7 (10.3)^{KU}

	Extra-Rotation	108.1 (1.9)^{NK}	105.6 (2.4)^{NK}	89.4 (1.7)^{KA,KU}	229.6 (22.7)^{NK,KA}	115.7 (20.1)^{KU}	166.8 (9.9)^{KU}
Hip	Flexion	122.4 (2.2)*	112.6 (3.3)*	82.1 (1.8)*	213.4 (15.0)^{NK,KA}	119.5 (20.1)^{KU}	100.7 (4.9)^{KU}
	Split	78.0 (1.5)^{NK}	76.5 (2.2)^{NK}	49.5 (1.7)^{KA,KU}	155.9 (8.6)*	105.0 (13.3)*	37.7 (2.8)*
	Sit and Reach	37.3 (2.5)^{NK}	36.7 (2.6)^{NK}	19.4 (2.1)^{KA,KU}	59.8 (6.9)^{NK}	51.0 (6.6)^{NK}	16.5 (2.4)^{KA,KU}
Ankle	Flexion	71.5 (1.1)*	80.5 (1.5)*	57.9 (2.0)*	96.5 (11.2)	80.1 (10.4)	121.3 (11.0)
	Overhead squat	29.2 (1.3)^{KA}	37.8 (1.3)^{KU,NK}	28.8 (1.0)^{KA}	32.6 (4.1)	34.0 (4.7)	24.5 (2.1)

Regarding the θ value for shoulder mobility, differences in all movements were found between the KU and NK groups (*p* always lower than 0.01), with the KU group showing the highest values for all movements. The only difference between KU and KA was found for the extension movement (*p*=0.03), where the KU group showed a greater value. In the same movement no difference was observed between KA and NK (*p*=0.45). Considering movement velocity, KU group was always associated with a statistically greater value of $\dot{\theta}$ than the other groups (*p* always lower than 0.01). In addition, KA showed the lowest value for all the movements also with respect to the NK. It can be observed that the values of the standard error of $\dot{\theta}$ were always greater when focusing on karatekas with respect NK.

By moving to the hip mobility, all the values of θ were statistically different between the NK and the karatekas (*p* always lower than 0.01); in these cases, the only significant difference between KU and KA was observed in the flexion movement (*p*=0.02), where KU showed greater values. The $\dot{\theta}$ parameter was always statistically different between KU and NK (*p* always lower than 0.01), whereas between KU and KA the differences were found for all movement (*p* ranged from 0.01 to 0.04) with the exception of the Sit and Reach (*p*=0.70). KA and NK showed no different behavior only for the flexion movement (*p*=0.12).

As regards the movements related to the ankle, values of θ obtained during the flexion movement showed significant differences among all groups (*p* ranged from <0.01 to 0.04); instead, no difference between KU and NK was found for the overhead squat (*p*=0.59). Generally, the KA group showed greater values for both movements. By moving to the velocity of the movements, no differences were found (*p* ranged from 0.07 to 0.53).

Mean values and standard errors of the angles computed during the joint mobility task performed at the maximum speed and the relative statistical results are reported in Table 2. Right and left values were considered together due to similar results between the two sides obtained in a preliminary analysis within each group.

Table 2 – Mean values (standard errors) for θ_{MV} and $\dot{\theta}_{MV}$ obtained during the joint mobility test performed at the maximum possible velocity for all the examined groups. KU, KA and NK stand for kumite, kata and non-karatekas group, respectively. Superscripts represent statistical differences, with * indicating difference among all groups.

		θ_{MV} (°)			$\dot{\theta}_{MV}$ (°/s)	
	KU	**KA**	**NK**	**KU**	**KA**	**NK**

Shoulder	Flexion	192.0 (1.7)^{NK}	190.2 (2.2)^{NK}	171.0 (1.8)^{KA,KU}	550.4 (18.9)^{NK}	491.1 (21.6)^{NK}	407.4 (12.9)^{KA,KU}
	Extension	100.9 (2.9)^{NK}	94.7 (2.4)^{NK}	80.8 (1.7)^{KA,KU}	378.8 (14.5)^{NK}	346.1 (21.6)^{NK}	234.2 (10.7)^{KA,KU}
	Abduction	179.2 (1.7)^{NK}	180.4 (1.8)^{NK}	162.0 (2.0)^{KA,KU}	522.3 (14.4)^{NK}	474.1 (23.9)^{NK}	392.9 (9.3)^{KA,KU}
	Extra-Rotation	117.6 (1.7)^{NK}	120.6 (2.7)^{NK}	96.2 (2.3)^{KA,KU}	529.4 (15.9)*	448.2 (17.8)*	354.7 (16.0)*
Hip	Flexion	139.5 (1.9)^{NK}	137.0 (3.2)^{NK}	94.7 (2.7)^{KA,KU}	331.5 (10.8)^{NK}	295.4 (14.1)^{NK}	190.3 (6.8)^{KA,KU}

Regarding the shoulder movement, karatekas showed θ_{MV} values always greater than NK (*p* always lower than 0.01), but no difference was showed between KU and KA (*p* ranged from 0.43 to 0.88). In addition, the $\dot{\theta}_{MV}$ parameter in all movements was statistically different between NK and the two groups KU and KA (*p* always lower than 0.01); while the only difference between KU and KA was observed in the extra-rotation movement (p=0.01), with KU associated to the highest average values.

By moving to the hip, statistical lower value of θ_{MV} was found related to the NK (p<0.01); instead no difference was found between the two karatekas groups (p=0.66). Similar outcomes were obtained for the $\dot{\theta}_{MV}$ related to the same movement.

Body Stability

Results related to the body stability tests were reported in Table 3. All participants were able to perform the test in EO condition. Conversely, as concerns the test performed with closed eyes, it is worth emphasizing that NK group was not considered in statistical tests since only three subjects of NK succeeded in completing test, while 15 subjects had to rest the contralateral limb during the execution of the test. For this reason, the comparisons among KU, KA and NK were performed only in the EO, whereas *t-tests* between KU and KA were conducted on the parameters related to EC test and on the RI.

As regards EO condition, statistical differences were found between KU and NK for the EA (p<0.01), PL (p=0.01) and PL_{AP} (p=0.01); while the only difference between NK and KA was observed for the $FREQ_{AP}$ (p<0.01). No significant differences were found between KU and KA (*p* ranged from 0.10 to 0.91).

By moving to the tests performed with closed eyes, no statistical differences were found between KU and KA (*p* ranged from 0.20 to 0.56). Finally, the Romberg Index computed for EA of KA was significantly lower in KA than the one computed for KU (p=0.02).

Table 3 – Mean values (standard errors) for the body stability tests for all the examined groups. KU, KA and NK stand for kumite, kata and non-karatekas group, respectively. Superscripts represent statistical differences. EO and EC indicate test performed with open and closed eyes, respectively. * Romberg Index is adimensional for each parameter.

	EO			**EC**		**Romberg Index***	
	KU	**KA**	**NK**	**KU**	**KA**	**KU**	**KA**
Path Length (cm)	48.9 (3.4)^{NK}	65.8 (8.7)	68.8 (4.7)^{KU}	119.0 (12.3)	120.9 (15.0)	2.4 (0.3)	1.8 (0.2)
Path Length AP	33.8	43.8	46.0	76.6	72.6	2.3	1.7

(cm)	(2.7)^{NK}	(5.4)	(3.1)^{KU}	(9.1)	(8.1)	(0.3)	(0.2)
Path Length ML	28.3	39.4	42.6	74.6	79.7	2.7	2.1
(cm)	(1.9)	(6.3)	(3.4)	(6.7)	(11.9)	(0.3)	(0.3)
Ellipse Area	36.4	55.4	92.7	179.0	204.9	9.1	3.9
(cm^2)	(7.4)^{NK}	(14.7)	(13.2)^{KU}	(38.3)	(47.0)	(2.4)^{KA}	(0.7)^{KU}
Frequency (Hz)	0.19	0.19	0.13	0.20	0.18	1.20	1.06
	(0.01)	(0.02)	(0.05)	(0.01)	(0.02)	(0.10)	(0.08)
Frequency AP	0.22	0.26	0.16	0.22	0.22	1.23	1.12
(Hz)	(0.02)	(0.03)^{NK}	(0.01)^{KA}	(0.01)	(0.03)	(0.12)	(0.16)
Frequency ML	0.23	0.24	0.16	0.26	0.22	1.32	1.17
(Hz)	(0.02)	(0.05)	(0.01)	(0.18)	(0.04)	(0.15)	(0.12)

Jumping Abilty

Mean values and standard errors of the indices related to the SJ, CMJ and RCMJ tests are reported in Figure 7 with related statistical differences.

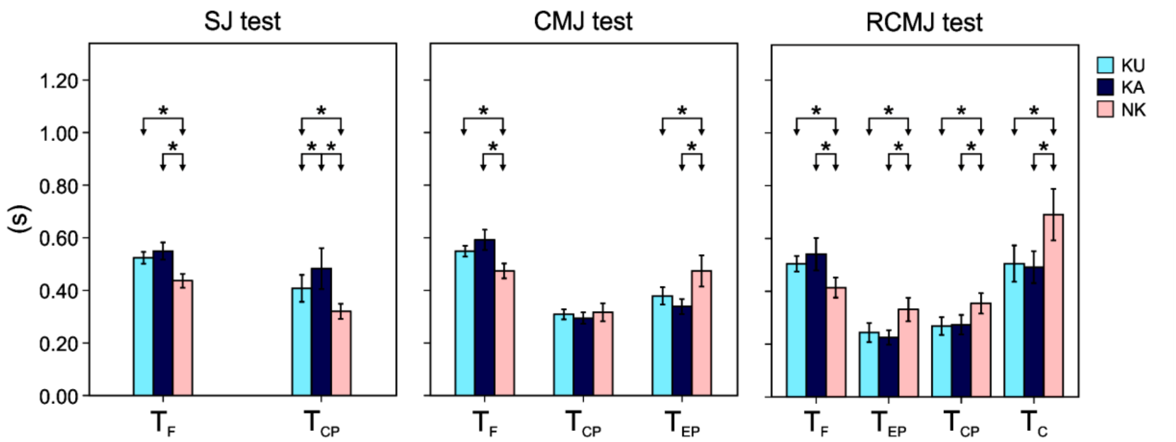


Figure 7. Mean values and standard errors of the parameters related to the jumping tests. From left to right: SJ, CMJ and RCMJ tests. Parameters: Flight Time (T_F), Concentric Phase Time (T_{CP}), Eccentric Phase Time (T_{EP}), and Contact Time (T_C). KU, KA and NK stand for kumite, kata and control group, respectively. * indicates statistical differences.

As regards SJ, T_F showed significant differences between the NK and karate athletes (*p* always lower than 0.01), with the NK having the lowest average value. Relatively to the T_{CP}, statistical differences were found among all the examined groups (*p* always lower than 0.01), with the KA showing the highest average value.

By analyzing CMJ, T_F and T_{EP} parameters showed statistical differences between the NK and the karatekas (*p* always lower than 0.01); specifically, NK showed the lowest values for T_F and the highest for T_{EP}. No significant differences were found between the two groups of karatekas. No difference among groups was found for T_{CP} (p=0.32).

By moving to the RCMJ test, statistical differences were found between NK and the karatekas for all the examined parameters (*p* always lower than 0.01). In particular, NK showed lowest average values for T_F and the highest ones for T_C, T_{CP}, and T_{EP}. No statistical difference was shown between karatekas (*p* ranged from 0.15 to 0.72).

Discussions

Joint mobility, body stability and jumping ability were assessed on sixteen kumite karatekas, eight kata karatekas and eighteen non-karatekas to: (i) assess the differences between karatekas and non-karatekas to provide guidelines for training programs in beginners; and, (ii) evaluate the differences induced by the karate technique on the above mentioned areas to provide suggestions for coaching programs addressed to elite athletes based on the specific karate technique.

Which are the kinematic characteristics that differ karatekas and non-karatekas? Is it possible to provide guidelines for training programs addressed to beginners?

By discussing the mobility results, the presence of statistical differences between non-karatekas and both karatekas' groups, with the only exception of the shoulder extension at the preferred velocity, allows affirming that joint mobility and agility is fundamental for the physical preparation of a karateka, as also reported in previous studies [18], [49]. More specifically, the greatest differences between karatekas and non-karatekas found for the shoulder and hip joints confirmed the results reported by Podrigalo *et al.*, who assessed as the two mentioned joints are the most involving in karatekas due to the punching and kicking specialization in martial arts [49]. Monopodalic equilibrium test revealed itself as a complex task and only karatekas were able to perform it in both open and closed eye conditions. This finding suggests that karate training considerably increases body stability [1]. As regards the jumping tests, the differences found between karatekas and non-karatekas for all the examined parameters confirmed as motor ability in jump execution represents one of the physical aspects to train in karatekas. In addition, the differences found for the RCMJ tests can be ascribed to an early occurrence of the fatigue effects in non-karatekas [50]. These findings are in line with the ones reported in [18]. We can speculate that jumping skills and resistance to fatigue are more developed in karatekas due to the specific training program addressed to the jump kicks [51].

Taking into account the above discussed outcomes, we can identify the physical characteristics to be trained in beginners in order to improve their motor performance in karate. Specifically, the differences found for all the examined motor abilities between karatekas and non-karatekas group lead to the conclusion that coaching programs addressed for karate beginners should stress the following aspects: upper and lower limb mobility, movement velocity, body stability and jumping ability. More specifically, it is clear as the shoulder and the hip represent the most important joints to train since they are the main actors in punching and kicking gestures, which are the main movements performed by a karateka during a competition [51]. This speculation is in line with the outcomes reported by [52], in which authors reported that the training of both the shoulder through throwing tasks and the hip by means of sit and reach tasks allows increasing joint mobility in primary school children. Concerning the movement velocity, beginners should pay attention on two aspects: the explosion of the movement, but also the control of the gesture; in fact, we have demonstrated as the movement velocity differs for the two techniques. From this perspective, training programs based on sound feedback have revealed themselves to be useful for the beginners [53].

In addition, it appears evident as the body stability in monopodalic task represents the weak spot of non-karatekas; thus, interventions focused on the improvement of stability also in single support condition should have explicit attention in beginners training sessions. In fact, it is demonstrated as monopodalic stability strategies are fundamental for providing upper and lower limb gestures with high intensity [54]. Finally, the right trade-off between eccentric and concentric phase, as well as flight and contact time, during jumping has to be carefully trained in order to improve the movement explosion during jump kicks [51]. As a conclusion, we can also suggest to constantly monitor these parameters to evaluate if the planned training programs are causing the desired improvements in the motor abilities. The acquisition of these knowledges can lead to overcome errors in teaching, especially in the initial period of training.

Which are the effects of karate techniques on joint mobility, body stability and jumping ability? Is it possible to provide guidelines for training programs addressed to elite athletes based on karate specialization?

The joint angles related to the shoulder extension, hip flexion and ankle flexion during the movements performed at the preferred velocity reveal themselves as the mobility indices that are more influenced by the karate technique. As regards the shoulder, the finding can be associated to the gesture required during kumite and kata competition. In fact, unlike the KU, the recall of the upper limb is not foreseen after a punch in the KA. Conversely, the recall of the upper limb, which requires a shoulder extension, represents a typical gesture of the KU after attacking the opponent; in fact, a penalty is assigned during official competition if the kumite athlete hits the opponent without calling the arm back [25]. The outcomes related to the hip flexion confirmed those reported in [18]. In fact, kumite athletes need a greater hip mobility since they must execute high kicks with an adequate velocity to defeat the opponent, instead kata athletes can perform more controlled movements. The lower values of mobility that KU showed with respect to the KA in the ankle joint can be justified by the different ankle movements required by the two discipline, and confirmed the results reported by [23]. During their competitive activities, kumite athletes are often on the forefoot by making small hops in order to optimize the reaction time in case of attack or defense [4]. Such behavior causes an almost constant eccentric-concentric stress on the muscles of the leg and, in particular on the triceps surae, leading to an increase of ankle rigidity and consequently to a reduction of the range of motion [55], [56].

As regard the movement velocity at the preferred speed, the lower value of velocity reported for the kata, with the exception of the ankle joint, is directly connected to the specialization required by the technique. In fact, KA athletes perform fine and controlled gestures during their exhibition. This difference was not confirmed in tasks performed with maximum velocity, suggesting that the lower velocity in mobility tasks performed at the preferred velocity for the kata athletes with respect to the kumite ones is effectively due to the technique rather than to less agility of the kata athletes. Nevertheless, the use of the velocity as a useful index should be deeply examined due to the high intra-group variability, which suggests a high heterogeneity also among athletes specialized in the same technique.

When dealing with to the body stability, the high values of standard error associated with all the parameters suggest that each karateka adopted a different strategy to complete the task regardless the specific technique. The absence of statistical differences between the two techniques is in contrast with the results reported in [1], in which kata showed greater stability than kumite athletes. However, it should be underlined that the observed better balance skills are related to bipodalic tests. A monopodalic test should be considered more appropriate to assess stability skills of a karateka since athlete is often in a single support position when kicking during the competition. Thus, the absence of statistical difference suggests that both techniques require a high level of body stability. The only parameter useful to differentiate the two karateka groups is the Romberg Index related to the ellipse area. The lowest value associated with the KA athletes described a better adaptation of KA group in performing balance tests without the aid of the visual apparatus. Thus, it is possible to assess that kata athletes develop stability skills mainly involving the proprioceptive inputs than the visual ones; instead, kumite athletes are useful to react to visual stimuli due to opponent movements both during training and competition. Thus, we can speculate that the KA athletes suffer less the lack of visual input in balance management [57].

The outcomes obtained from the jump test analyses allow affirming that the two techniques do not lead to different motor performance in jumping due to the general absence of statistical differences between kata and kumite athletes. The only useful parameter seems to be the duration of the concentric phase during squat jump, which KA group showed a longer duration than KU. This result can be ascribed to the starting position of KA athletes characterized by a greater value of the knee angles, leading to deeper squat than the KU athletes. The different starting position can be justified considering two factors. Firstly, it can be linked to the different ankle mobility previously discussed, allowing to reach a lower starting position for the jump for the kata. Secondly, it can be attributed to the different specialization due to the discipline as KA athletes often assume squat positions, similar to SJ, when a push phase is needed from an isometric situation [58].

Considering the above discussed outcomes, we can speculate that a single wearable sensor and the use of optoelectronic bars can allow to provide synthetic indices useful to monitor karate specialization and to focus coaching programs for emphasizing the motor abilities required by the specific karate technique. Focusing on joint mobility, kumite athletes should focus their attention mainly on the shoulder mobility, especially related to the extension movement; instead, kata should stress the training of the ankle mobility. Even though the ankle mobility is shown as one predictive factor, we can speculate that also kumite athletes should take into account the training focused on the ankle mobility; in fact a poor mobility, *i.e.* joint rigidity, can lead to a worsening of the performance during jumping, as found in the examined jumping tests and also reported in [59]. Furthermore, it has already been demonstrated as an excessive of ankle rigidity can lead to an increase of injuries [60]. From the same perspective, it would be useful the introduction of specific training sessions addressed to increase the ankle mobility during the training programs of kumite athletes, for example through BHC and BCS programs that allow improving ankle mobility with respect traditional calf stretch technique [61]. In addition, kata training should have specific attention to the control of the movement by avoiding uncontrolled gesture during competition [25].

Assessment of cognitive skills in karatekas pre-post technical training

Introduction

Cognitive functions are skills organized by the brain in order to regulate the relationship with the external environment. These skills are acquired from birth and they must be constantly strengthened over time and, in case of advanced age, also re-enabled. Typical cognitive functions are attention, memory, orientation, language, visuospatial skills, praxic skills and executive functions. These tasks are often classified as simple, if they require very simple perceptual motor skills e.g. choice of reaction time, or complex, in case they require more effort and/or attention, such as multiple/double tasks e.g. complex motor coordination, working memory tasks [62,63]. Many scientific studies have shown how physical activity positively influences the development of cognitive functions in different age groups; in addition, it has been demonstrated how the cognitive training can have a positive effect on progresses of different pathologies [64,65]. In recent years, several studies have been conducted to understand how these abilities vary in relation to physical activity also in élite sports. This particular attention is ascribed to the knowledge that sports practice, especially at a high level, requires an ever greater increase in the performance of athletes, also form a cognitive point of view; thus encouraging the search for variables to improve the chances of success in competition [63,66]. For example, in team sports it has been shown that it is very important to evaluate and monitor cognitive functions, as well as physiological and biomechanical functions, to better manage the performance of a team during the competition period [67].

The most common team sports are situation sports where the conditions in which the athlete is immersed change constantly, so to achieve their goal, each athlete must be able to shift their attention to the most useful points to select and extract useful information from the environment in order to understand the future actions of both opponents and teammates. For example, basketball or football players need to quickly understand what is happening around them because they have to make the best decision to choose whether to anticipate or wait for the opponent to run. To do this, athletes must focus, analyze and recognize any movement long before any action is taken [68]. The same is true for combat sports such as boxing, karate, taekwondo and judo that are not excluded from these demands; being an open-skill sport where the context in which the athletic performance takes place is not predictable and can change during the event. For this reason, the athletes must coordinate and interact with external opponents and know how to adapt to a new context [68]. Specifically, in the world of sports research, studies have focused on the effects of physical fatigue on cognitive functions [69,70] to understand how much and how this can affect the athlete's response and on the effects of cognitive fatigue on athletic performance [71,72]. In particular, most of the works in recent years have focused on analyzing the effects of physical fatigue on cognitive functions after very intense workouts such as High Intense Interval Training, Tabata or in any case high-intensity workouts whose duration was less than 60 minutes [73] or exercise sessions of longer duration but at sub-maximal intensities [74].

Focusing on karate, few studies have been carried out in this field and often with conflicting results. Recently, Dwojaczny *et al.* [75] evaluated the effects after a long period of karate training on cognitive performance by testing a group of young karatekas and a control group, asking them to perform the face/name association test, stroop test and trail making test, finding a reduction in cognitive functions for the karatekas. Carrying out similar cognitive tests, no significant difference between the three-month pre and post-tests was found by Jansen and Dahmen-Zimmer [76] on a population of older people undergoing karate training. Recently a similar work was carried out by Witte *et al.* [77] with different results, in fact, improvements in cognitive functions were found on an elderly population, compared to a control group, when subjected to five months of karate training. Again, tests such as memory formation by word list, number transcoding, semantic word fluency task, attention by digit span reverse, and delayed recall of word list were used.

To the best of the author's knowledge, no study has ever investigated how a single specific technical training can influence the cognitive functions of a group of high-level athletes in the short term and in particular in a concentration and speed sport such as karate. Furthermore, all the studies analyzed propose verbal, written or manual assessment methods for cognitive functions. The aim of this study is therefore to investigate whether a technical karate training can modify the cognitive functions of high-level karate athletes by measuring cognitive functions through an innovative digital technology. The results of this work could be useful to coaches and athletic trainers to better calibrate the workload during technical training or develop ad hoc training for cognitive functions.

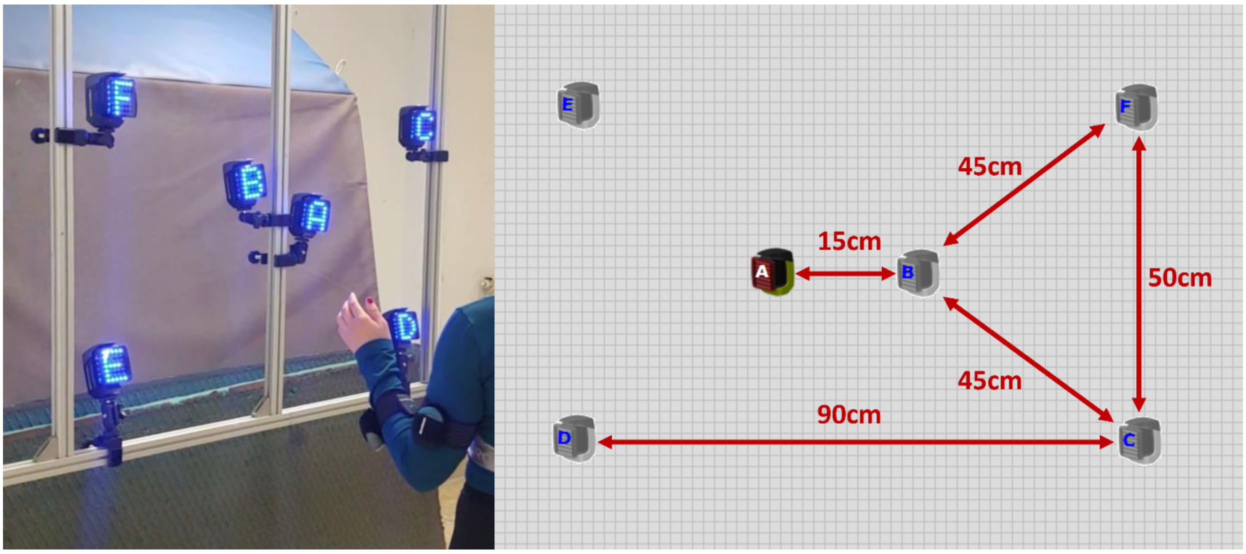
Materials & Methods

Participants

Eleven international level karatekas (5 men and 6 women) with at least 15 years of practice and belonging the Italian national karate team were involved in the study. All of them were kumite athletes (age = 22 ± 3 years, height = 169.4 ± 7.6 cm, body mass = 64.8 ± 9.4 kg). The Dominant limb (D) was identified for each athlete by asking the subject which limb was used for the usual guard position. Among them, there were winners of the Italian championship, European champions and World champions in the different weight categories. All of them were involved in karate six days per week and twice for each day and they had no injuries at the time of testing. All participants were informed on the rationale of the study and a written informed consent was obtained according to the ethical standards outlined in the 1964 Declaration of Helsinki.

Experimental Setup

The WittySEM photocell system made by Microgate Srl (Bolzano, Italy) was used for the analysis of cognitive functions. The system consists of 6 photocells, each of them with an optical proximity sensor and a 7x5 LED matrix capable of managing different colors, arrows in different directions, numbers, letters and other symbols. The proximity sensor allows the athlete to interact with the photocell by bringing the hand closer to about 10 cm without having to touch it. A tablet (WittyTIMER) manages all the photocells via radio communication in real time for the acquisition of the times and responses of the athletes. This system is currently widely used in sports especially for the evaluation of tasks such as the change of direction on field or for the training of athletes [78,79]. The photocells can be positioned in various ways (on tripods, on magnetic supports, on floor suction cups, etc.) depending on the chosen exercise, for this study they were mounted on a structure using clamps as shown in Figure 1a. As reported in the Figure 1b, the distance among photocells were standardized during the experimental protocol.



a) **b)**

Figure 8. Positioning of WittySEM (a) and distance among photocells (b).

Technical training

The technical training session lasting about 75 minutes included an initial phase of 10 minutes of muscle warm-up, then the coach in a couple of minutes explained to the athletes the fist and kick techniques to be applied during training. At this point the athletes for a duration of about 15-20 minutes first trained alone and then with a partner to put the techniques into practice. Halfway through training the coach gathered the athletes around him again to show them some typical racing situations and then work on the attack and defense phases.

Until the end of the training, the athletes worked with one partner at a time, exchanging each other, to work on competition situations. Once the training was completed, the athletes underwent the experimental protocol.

Experimental Protocol

The experimental protocol consists of three types of cognitive exercises: a test of response time (RT), a visual attention (VA) and a brain speed (BS) test.

Response time - RT

The RT is a test where the athlete must go to "turn off" the photocell as quickly as possible by following a pre-established symbol, in this case a green rectangle has been chosen. The RT test is a procedure for measuring the time elapsing between a stimulus received by a subject and the response emitted by himself [80]. The athlete is positioned in the guard position, at a distance of 30 cm from the structure, and "turns off" the target symbol with only the hand placed forward in the guard position, the test is performed in both guard positions, therefore with the dominant (D) and non-dominant (ND) limb. The target symbol after being "turned off" by the athlete reappeared with a delay of 100 ms. The test ends after the athlete has "turned off" all 30 target symbols. The lighting sequence of the target symbol is preset and is always the same for all the RS tests, this sequence was created using the Witty Manager software (Microgate Srl, Bolzano

IT), this choice is given by the need to standardize the sequence among the different athletes in order to be able to subsequently compare the results. It is worth noticing that in this case the athletes were not aware of the standardization of the sequence. This test was divided into two modes, one easy (RTE) and one difficult (RTD). In RTD a noise element has been added, which is represented by blue and/or red rectangles that can randomly appear together with the green rectangle.

Visual Attention - VA

The VA test aims to investigate the capacity of the subject's "useful visual field" and the speed with which it is able to discriminate the details when the gaze must be focused centrally [81]. In the VA test the athlete is positioned at a distance of 2 m from the structure with the photocells. The exercise is made up of 30 visual impulses and is structured in this way: on the two central photocells 2 blue cars or 2 blue trucks are shown and at the same time a small blue square is shown on one of the peripheral photocells. The initial time with which these symbols are shown is 1000 millisecond.

Once the visualization is complete, the photocells switch off and then both the car and the truck are shown on the central photocells, at this point the athlete must select, by putting his hand near the photocell, if cars or trucks had appeared before. If the answer is correct, the athlete must also select on which of the peripheral photocells the small square had appeared and then return to the initial position. If the athlete provides these two correct answers twice consecutively, the system automatically lowers the subsequent display time, making the exercise more difficult, up to a display time of 32 ms. From the initial step of 1000 ms there are ten steps to arrive at the final step of 32 ms. Table 4 shows the ten steps with the associated display time.

Table 4 – Steps and displayed time.

Number of Step	Displayed Time [ms]
0	1000
1	708
2	501
3	355
4	251
5	178
6	126
7	89
8	63
9	45
10	32

On the contrary, with each error the display time increases by one step, making the exercise easier [82-84].

Brain Speed - BS

The BS test investigates how quickly the brain can process events around the subject and determines how effectively he can react and remember those events [85]. In the BS the athlete is positioned as in the VA test and the number of visual impulses is the same, i.e. 30. In this exercise the system displayed six symbols of the same shape for a certain period of time but a symbol on a photocell had a slight color different. The initial time with which these symbols are shown is 1000 millisecond.

Once the visualization is complete, the photocells switch off and at this point the athlete must select, by putting his hand near the photocell, where the symbol with the different coloring was. If the athlete provides two correct answers twice consecutively, the system automatically lowers the subsequent display time, making the exercise more difficult, up to a display time of 32 ms. The same sequence of steps used for the VA was used for BS. On the contrary, with each error the display time increase by one step, making the exercise easier [82-84].

With each of the athletes a familiarization session was performed on all the exercises the day before the test and to avoid further learning by the athletes [86] the familiarization session was carried out with the presence of one athlete at a time. The cognitive exercises were randomly administered to each athlete with the only exception being to perform the RTD tests after the RTE ones. The protocol provides for the execution of cognitive exercises before the start of the technical training session and immediately after the end of it. In order to avoid the recovery of the athlete from fatigue, only two athletes were tested for each session using two separate stations.

Data Analysis

RT data were firstly tested for normality with the Shapiro Walking test. RT data comparisons were made using a paired samples T-test to elucidate statistical differences. Data collected in VA and BS tests were analyzed with Wilcoxon's two-sample dependent non-parametric test. Statistical significance was set at $p < 0.05$ for all the performed tests.

Response Time

For the statistical analysis of the RT, all the times that each athlete took to complete the two RTE and RTD sequences with both D and ND were acquired. Each athlete had performed eight tests, four in the PRE and four in the POST. In total, eighty-eight RT tests were acquired. Forty-four tests for the RTE and forty-four for the RTD, divided in turn by twenty-two tests for the PRE training and twenty-two for the POST training. The data of D and ND in the PRE and POST training situations in the RTE and RTD tests were then compared. Finally, comparisons were also made between the D and ND results in the PRE and POST situations for the two sequences.

Visual Attention and Brain Speed

In the VA and BS test, the total number of errors (NE) committed by each athlete were considered and the results compared between the PRE and POST situations. Subsequently, the values relating to the maximum step ($STEP_{max}$) reached during the test and the value of the step reached at the end of the test ($STEP_{final}$) were analyzed. Finally, the number of consecutive correct answers (CCA) was calculated from the start of the test until the first error.

Results and Discussions

Table 5 shows the results related to the RTE and RTD tests and the relative significance values between PRE and POST training and between D and ND in PRE and POST training.

Table 5 – Means and standard deviations of D and ND results for RTE and RTD in PRE and POST training. * indicates significant differences.

	RTE				**RTD**			
	D		**ND**		**D**		**ND**	
	PRE	*POST*	*PRE*	*POST*	*PRE*	*POST*	*PRE*	*POST*
Mean (SD) [s]	14.75 (1.50)	13.61 (0.89)	14.98 (1.50)	13.69 (0.75)	18.56 (1.40)	18.01 (1.56)	19.10 (2.08)	18.29 (1.74)
p-value	***<0.01****		***<0.01****		*0.06*		*0.07*	
	PRE		**POST**		**PRE**		**POST**	
	D	*ND*	*D*	*ND*	*D*	*ND*	*D*	*ND*
Mean (SD) [s]	14.75 (1.50)	14.98 (1.50)	13.61 (0.89)	13.69 (0.75)	18.56 (1.40)	19.10 (2.08)	18.01 (1.56)	18.29 (1.74)
p-value	*0.37*		*0.77*		*0.13*		*0.51*	

Considering the significant differences between PRE and POST training in RTE and RTD, they emerged only in the RTE in both D and ND, $p = 0.002$ and $p = 0.005$ respectively. In the case of the RTD the results show a trend towards significance for both D and ND, $p = 0.056$ and $p = 0.074$ respectively. Due to the lack of work performed so far on this topic and with a similar technology, it is difficult to compare the results of this study with other works. Results similar to the present work were found by Mroczek *et al.* [87], who found an improvement in response times with a significant 13.3% decrease from pre-match values on volleyball players after one set of play. Furthermore, Malhotra *et al.* [88] observed that visual reaction time was significantly lower after performance of exercise on active people, similar results were obtained by Bergelt *et al.* [89] who found greater accuracy and speed of response times after moderate intensity aerobic training on healthy adults.

On the contrary, Jader Sant'Ana [90] found no difference in response times following the effects of fatigue in taekwondo athletes by performing pre- and post-training tests, instead finding differences in reaction times and in the impact strength of the kick, their protocol, however, did not provide technical training. Pavelka [91] also found negative effects on response times after intense physical exercise on mixed martial arts athletes but even in this case it was not a technical training and reaction tests were carried out using a finger that had to press on a button. The lack of standardization in the results in terms of effects on cognitive skills due to the fatigue induced by training can be ascribed by the different tested exercises. In fact, Abd-Elfattah *et al.* [74] suggested that the effect of physical exercise on cognitive performance depends on both the intensity and the duration of the exercise, suggesting that the relationship between acute physical activity and cognitive performance has an inverted U shape. Some reported that physical exercise of moderate intensity and duration appears to ameliorate brain dysfunction. In fact, several studies found that immediately after an exercise session of sub-maximal intensity (i.e., heart rate of about 110–130 beats per minute) and a duration of 20–40 min, there is an improvement in sensors-motor and cognitive performance. As regards the present study, it is possible to speculate that the technical training carried out by the karatekas positively affects the response times of the athletes when the task is simple, whereas this positive influence tends to disappear when the task becomes more complex.

Focusing between D and ND there are no significant difference emerged. This result is in line with the values obtained by Cojocariu [92], who found no differences between dominant and non-dominated limbs in the RT. This almost equal attitude in both upper limbs in high-level athletes can be attributed to specific training that involves both sides of the body, resulting in a noticeable improvement in the response time chosen even in the non-dominant hand. Thus, athletes acquire the ability to effectively use the non-dominant hand in combat, increasing their chances of victory.

Tables 6 and 7 show the results for VA and BS respectively.

Table 6 - Results of the VA, for each subject the total number of errors (NE), the final level ($STEP_{final}$) and the maximal level ($STEP_{max}$) reached, and the number of consecutive correct answers (CCA) are indicated for the PRE and POST training. * indicates significant differences.

VA	**NE**		**$STEP_{final}$**		**$STEP_{max}$**		**CCA**	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST
Subj1	6	6	5	5	5	5	8	8
Subj2	7	8	2	1	5	6	5	12
Subj3	5	5	6	6	7	6	9	8
Subj4	6	6	5	4	6	6	10	9
Subj5	8	7	2	4	5	4	9	9
Subj6	5	5	7	7	6	7	4	3
Subj7	6	5	5	6	5	6	10	6
Subj8	7	6	4	4	5	5	8	6
Subj9	6	7	5	4	5	5	10	6
Subj10	6	4	4	8	4	8	13	13
Subj11	6	7	5	4	5	5	5	10
p-value	*0,53*		*0,73*		*0,32*		*0,67*	

Table 7 - Results of the BS, for each subject the total number of errors (NE), the final level ($STEP_{final}$) and the maximal level ($STEP_{max}$) reached, and the number of consecutive correct answers (CCA) are indicated for the PRE and POST training. * indicates significant differences.

BS	**NE**		**$STEP_{final}$**		**$STEP_{max}$**		**CCA**	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST
Subj1	3	4	9	8	9	8	15	14
Subj2	0	0	10	10	10	10	21	21
Subj3	4	2	7	10	7	10	9	12
Subj4	0	1	10	10	10	10	21	18
Subj5	4	5	8	6	9	8	10	19
Subj6	2	4	10	8	10	9	15	15
Subj7	4	4	8	8	8	9	4	13
Subj8	3	1	9	10	9	10	13	16
Subj9	3	0	9	10	9	10	10	21
Subj10	5	0	7	10	8	10	8	21
Subj11	1	2	10	10	10	10	16	16

p-value	*0,47*	*0,61*	*0,27*	***0,05****

In both tests the only significant difference between PRE and POST training emerges for CCA in the BS ($p = 0.049$). The only difference that emerged in the BS concerns the fact that the karatekas made the first mistake after having made a greater number of correct answers and therefore arriving first to carry out the task at a more difficult level, it is possible to speculate that technical training in this case had positive effects on the concentration of the athletes, however, for both the BS and VA tests there were no negative influences from the technical training in any of the parameters analyzed. Also, with regard to cognitive ability there is a lot of discord in the literature as evidenced by Leahy *et al.* [73], the results of their analysis support the "cognitive stimulation hypothesis" i.e. that activities that are coordinatively demanding, stimulate similar areas of the brain that are responsible for higher-order cognitive processes. Benefits may arise from physical activity that is “cognitively demanding” such as karate where athletes have to constantly learn new techniques.

CONCLUSIONS

The first chapter focused on the evaluation of motor and cognitive skills of a combat sport such as karate practiced by elite athletes.

Through the aim of quantifying the effects of different karate techniques on motor performance, joint mobility, body stability and jumping ability were assessed analyzing twenty-four karatekas and eighteen non-karatekas healthy subjects. A single inertial sensor and optoelectronic bars data were used to acquired data during the execution of specific tasks. Karatekas showed better motor performance in terms of joint mobility, body stability and jumping ability than non-karatekas. Mobility outcomes reveal themselves as the most influenced by the specific karate techniques, especially when looking at shoulder and ankle joints. The greater ankle mobility of kata than kumite also leads to a better performance in jumping. Kata athletes are, finally, performing better than kumite athletes when monopodalic stability tests are executed with closed eyes. These findings can be useful for coaching program implementation addressed to both beginners and karatekas who want to reach elite level in a specific technique.

The aim of the second part of the work was to investigate how a single specific technical training can influence the cognitive functions of a group of high-level athletes in the short term by measuring cognitive functions through an innovative digital technology.

Thanks to the results obtained, it is legitimate to state that for the evaluated parameters there are no negative influences on athletes given by technical training. In fact, as regards the response time tests, the athletes showed improvements after technical training and no differences emerged on specific cognitive functions. Furthermore, for the first time an innovative technology was used for the evaluation of these capacities, useful for developing new working protocols for sector technicians.

Finally, the results obtained can be used to improve the quality of training for elite karatekas.

Related published paper

- **Molinaro, L.**; Taborri, J.; Montecchiani, M.; Rossi, S. Assessing the Effects of Kata and Kumite Techniques on Physical Performance in Elite Karatekas. *Sensors* 2020, 20, 3186

2. ANALYSIS OF NEW PREDICTIVE INDICES FOR ACL INJURY IN BASKETBALL AND FOOTBALL

Identification of new pre-injury indices via a basketball ACL injury case study

Introduction

Among the most practiced sports in the world, basketball counts more than 450 million players ranging from the amateur to the high-level professional. Basket is characterized by to the development of high forces in short spaces and times, and by a constant contact among players; thus, it is a sport with a high risk of injury, as it has already been demonstrated by [93-95]. Among the most widespread and dangerous injuries is the anterior cruciate ligament injury of the knee (ACL). In fact, it can reduce the ability to express intensity and skills before injury and leads to prolonged absences from the playing fields [96-98]. In particular, women are 2 to 8 times more likely than men to develop an anterior cruciate injury [99-101]. Generally, ACL injuries are attributed to physiological, anatomical and biomechanical risk factors which, in particular in the pubertal phase and together with an incorrect technical gesture, can cause abnormal joint stresses, especially in landing from the jump during the phase in which the limb stabilizes [102]. Incorrect landing biomechanics can persist throughout puberty and can persist as the athlete matures [103-107].

Prevention of ACL injury should be based on integrating neuromuscular training and plyometric exercises into basketball players' training routines to improve joint control and stability and, consequently, reduce the risk of lower limb injury. For example, some authors have highlighted how the risk of dynamic valgus knee is reduced after only 4 weeks of specific training [108-112]. Primary prevention, therefore, must consider coordinated training integrated into training as much as it is specific to sport [113-115] which also includes adequate and constant communication between medical and technical personnel, which is essential for obtaining positive results and avoiding injuries or relapses [116]. From this point of view, there have already been many studies aimed at identifying predictive factors for ACL injury. More specifically, Myer *et al.* showed how the abnormal increase in knee abduction moment during landing could be useful in identifying athletes at higher risk of injury. The tests performed through the optoelectronic system have allowed to reach an accuracy of prediction up to 90% [117]. Similar results were obtained by Landis and colleagues by analyzing through video the drop-jump landing test performed by 180 athletes from different sports, such as handball, basketball, volleyball and football [118]. Bond *et al.* compared the traditional Functional Movement Screen (FMS) with an innovative tool for the prediction of LCA injuries, called the Basketball-Specific Mobility Test (BMT), finding that both procedures do not allow to achieve good performance, i.e. area under the ROC curve less than 0.60 [119]. Measurement of hip abduction and external rotation force has been suggested as predictors of ALC injury by [120] after studying the behavior of more than 600 athletes. The main problem of the studies listed above was related to the optoelectronic systems adopted; in particular, they are expensive, time-consuming and measurements can only be performed in the laboratory [121].

Recent technological innovations have made data analysis faster and easier when performing the technical gesture in sport-specific environments. Among the most used technologies, inertial sensors are the most appropriate for performing gestural analyzes in the field [122-125]. Janssen *et al.* validated the use of inertial sensors to acquire the kinematics of athletes during jumping tests, evaluating that the valgus excursion on impact with the ground can be considered a predictor for the prediction of ACL injuries [126]. Dowling and colleagues proposed a wearable system based on inertial sensors to assess the risk of ACL injury by finding useful information in analyzing the knee flexion angle when the foot reaches the ground after a jump [127].

However, as far as the authors are aware, there are no studies in the literature for the evaluation of predictive factors based on the stability of the leg during the stabilization time after the jump and not only during the contact phase of the foot with the ground. Furthermore, quantitative measures based on inertial sensors have not been proposed so far to monitor the time to return to competition of injured athletes. Therefore, the objectives of the present study are twofold. First, we studied the ACL risk factors detectable with a wearable inertial system placed on the leg by calculating the stability indices relative to the shank. Second, we investigated whether the proposed stability parameters are useful in providing quantitative measurements to correctly select athletes' return-to-play time after surgery. In particular, the results are based on a case study of an under 14 national competitive basketball player involved in a one-year prospective study.

Materials and Methods

Case study

A subject practicing basketball at a competitive level for the National Under 14 women's team was included in an observational study of the duration of two consecutive competitive seasons. The athlete was subjected to four sessions of clinical and instrumental tests. The acceptance of informed consent by the parents or tutor of the child was requested by a written consent following a presentation meeting of the methods and objectives of the study. Experimental protocol was in accordance with the 1964 Helsinki Declaration. The injured participant suffered the left knee injury during an international basketball match, which took place a month after the first evaluation session. The diagnosis was the ACL rupture in the left knee, which occurred during an atraumatic single-leg landing with a pivot-shift mechanism of the knee. In the month preceding the day of the ACL injury the girl had performed trainings only 10 times due to a sprained right ankle trauma. Then, the athlete underwent an ACL reconstruction with hamstring autograft. After a 6 months-rehabilitation, the federal doctor authorized the return of the girl in training and competition activities.

Experimental setup

The GYKO inertial sensor system (Microgate SrI, Italy) consists in a single MIMU (dimensions: $50 \times 70 \times 20$ mm, mass: 35 g) that contains three-dimensional accelerometer, gyroscope, and magnetometer with an acquisition frequency of 1 kHz. The GYKO inertial sensor was fixed in correspondence with the middle back third of the leg using the semi-elastic belt supplied and the specific magnetic support for the device to avoid its mobilization during the tests. During the evaluations, the GYKO signals were simultaneously transferred via Bluetooth to a personal computer and saved with the OPTOGait software.

An OPTOGait optoelectronic bar system was synchronously associated to the GYKO in order to estimate the time of flight (ΔFT) and contact time (ΔCT). The OPTOGait system (OPTOGait, Microgate S.r.I, Italy, 2010) consists in transmitting-receiving 1 m long bars positioned above the ground. Each bar is equipped with ninety-six LED diodes. Four OPTOGait bars were placed in parallel on the ground and connected to each other to form a space of 2 m in length and 2 m in width. Finally, two cameras (Logitech C920 HD) synchronized and placed at about 2.5 m from the participant were used to record the entire experiments. The experimental setup was shown in Figure 9.

Figure 9. Experimental setup

Experimental protocol

The athlete was asked to wear clothes she usually trains with. After few minutes of standard warm-up, the athlete proceeded to perform the Single-leg Drift Jump Protocol (SLDJP) instrumental test, which consists in 5 consecutive, monolateral, vertical jumps. The test was performed both with the dominant and contralateral limb [128]. Dominant leg was assessed by asking to kick a ball [129,38]. More specifically, the athlete was asked to reach the single-leg starting position and, after an acoustic signal, to perform five maximal single-leg jumps with her arms free to move. The entire procedure, consisted in preparation, measurements and recordings took 10 minutes in total. The evaluation of jump landing was performed in four different sessions; the first one before the injury and the remaining three after the rehabilitation program, specifically after 7, 10 and 14 months from the surgery.

Data processing and analysis

Several instrumental parameters of the SLDJP were analyzed on each leg in order to highlight any differences at the jump landing between the healthy lower limb (HL) and the injured one (IL). We defined the stabilization time ($\mathbf{t_{st}}$) as the temporal distance between the foot contact with the ground detected by the Optogait bars (CTstart) and the first minimum of the absolute value of the shank’s angular velocity, named as ω min (Figure 10).

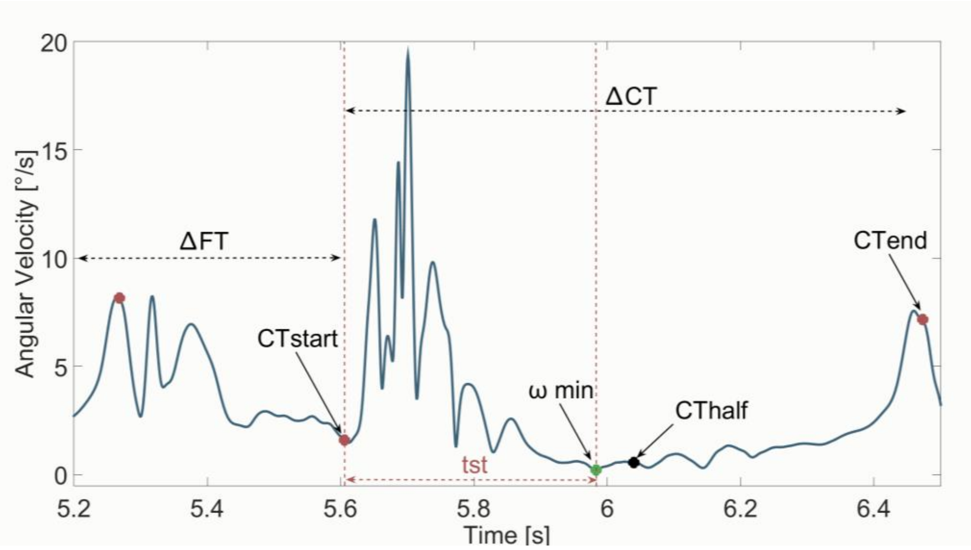


Figure 10. Identification of the stabilization time (t_{st}). ΔCT is the Contact Time, ΔFT is the Flight Time. CTstart, CThalf and CTend represent the initial instant, the half one and the end of the contact phase, respectively.

After the stabilization time computation, several parameters related to the leg stability were calculated during the t_{st}. In particular, the roll and pitch angles derived from the acceleration and angular velocity signals gathered with the GYKO were used to calculate the stability indices. Shank stability indices were analyzed during the stabilization time by considering the projection points of the $\vec{P}$ vector parallel to the shank on a horizontal plane placed at 1 cm from the inertial system. We studied the path covered by the $\vec{P}$ projection points by means of parameters typically used in posturographic analysis: Ellipse Area (EA); Path Length (PL); Anterior-posterior path length (PL_{AP}); Middle-lateral PATH length (PL_{ML}); Speed (V) and Frequency (F). More specifically, by following equations reported in [45], the Ellipse Area was computed as the 99% confidence ellipse area that is the area of the 99% bivariate confidence ellipse, which is expected to enclose approximately 99% of the $\vec{P}$ path. The path length represents the total length of the $\vec{P}$ path and it was also computed by separately considering anterior-posterior and middle-lateral components. The speed represents the average velocity of the $\vec{P}$ projection points. Finally, the frequency is the ratio between average velocity and mean distance of $\vec{P}$ projection points. Greater values of EA, PL, V, and F indicate a greater instability of the shank during the stabilization time after the jump landing; in fact, greater values of these indices are related to an increment of the oscillation of $\vec{P}$ [130]. More specifically, greater values of EA and PL indicate an increase in the $\vec{P}$ displacement; while V and F an increase of the $\vec{P}$ displacement velocity [45]. It is worth noticing that the increase of instability immediately after jump landing is considered as one of the main causes of ACL injury [130].

Means and standard deviations of each parameter were computed across the five jumps performed during the SLDJP for all sessions and both lower limbs.

Statistical analysis

The data was analyzed using the IBM SPSS for MAC v. Application. 25 (IBM SPSS Inc., Chicago, II). All data was tested for normality by the Saphiro-Wilk test. The values of the parameters related to the right and left lower limbs obtained in the pre-surgery assessment were analyzed through a paired t-test in order to evaluate significant differences between the two sides before the injury. Such likely statistical differences could allow identifying potential predictive factors for ACL injury.

Finally, a one-way ANOVA test was used to evaluate differences in the injured leg among the pre-injury assessment and the three post-surgery ones in order to identify parameters able to quantify the correct time for the return to competition of the athlete. A *p-value* lower than 0.05 was considered significant for all the performed analyses.

Results & Discussions

As a paradigmatic example, Figure 11 show the graphs along the directions AP and ML of the ground projection of $\vec{P}$ following the landing of the jump during the $\mathbf{t_{st}}$. In particular, the figure refers to the first of the five performed jumps with the injured leg in the pre- and post-surgery sessions, respectively.

By analyzing the figure, it can be observed that the $\vec{P}$ path presents greater oscillations in the pre-surgery session with respect to the post-surgery one, especially in the ML direction. This result can be associated to the inability to control the forces generated during the impact with the ground when the jump is performed with the leg that will occur in the ACL injury.

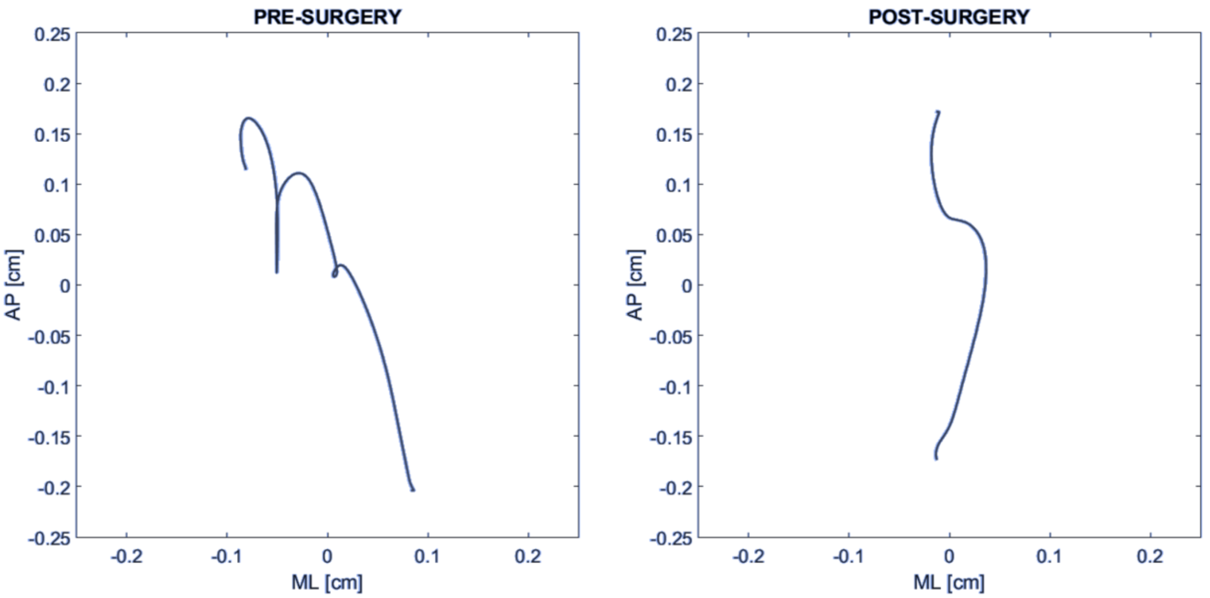


Figure 11. $\vec{P}$ path following the landing of the first jump performed with injured leg in the pre-surgery test and post-surgery test.

Mean and standard deviation related to IL and HL obtained in the pre-surgery assessment are reported in Table 8 with the relative statistical differences.

Table 8 - Mean (SD) of the instrumental parameters related to the pre-surgery assessment for both IL (injured leg) and HL (healthy leg) grey cells indicate statistical differences.

Parameters	**IL**	**HL**	***p-value***
$\mathbf{t_{st}}$ **[s]**	0.23 (0.03)	0.18 (0.06)	*0.23*
EA [cm^2]	0.16 (0.04)	0.10 (0.01)	*0.04*
PL [cm]	0.82 (0.12)	0.45 (0.07)	*<0.01*
$\mathbf{PL_{AP}}$ **[cm]**	0.71 (0.09)	0.39 (0.07)	*<0.01*

PL_{ML} [cm]	0.31 (0.08)	0.19 (0.01)	*0.03*
V [cm/s]	0.73 (0.14)	0.63 (0.14)	*0.18*
F [Hz]	1.12 (0.22)	0.94 (0.12)	*0.16*

The posturographic parameters EA, PL, PL_{AP}, PL_{ML}, showed significant differences of the injured lower limb compared to the contralateral lower limb in the pre-surgery evaluation. More specifically, statistical greater mean values were always associated to the lower limb that suffered of the injury one month later the assessment.

This could be interpreted with a greater instability of the injured lower limb at the time of landing from the jump, which could imply a greater risk of injury. These findings confirm the ones reported by other studies, suggesting that the instability during jump landing or turning movement can increase the risk of ACL injury [131]. From these outcomes, we can affirm that periodic assessments of the leg stability during jump landing should be adopted in order to monitor athlete at higher risk, leading to a prediction of the injury events, and to implement customized training programs during coaching for improving the stability.

Table 9 shows means and standard deviations related to IL obtained for the pre- and post-surgery assessments compared with the parameters computed for the healthy leg.

Table 9 - Mean (SD) of the instrumental parameters related to the pre-surgery assessment and the three post-rehabilitation ones computed for the injured leg (IL). The last column represents the mean value and standard deviation related to the health leg. * indicate the presence of statistical difference among the post-rehabilitation assessments and the pre-injury one.

	IL				HL
Parameters	**Pre**	**Post1**	**Post2**	**Post3**	
t_{st} [s]	0.23 (0.03)	0.13 (0.04)*	0.11 (0.02)*	0.10 (0.03)*	*0.18 (0.06)*
EA [cm2]	0.16 (0.04)	0.13 (0.04)*	0.11 (0.02)*	0.10 (0.03)*	*0.10 (0.01)*
PL [cm]	0.82 (0.12)	0.39 (0.04)*	0.41 (0.11)*	0.35 (0.05)*	*0.45 (0.07)*
PLAP [cm]	0.71 (0.09)	0.27 (0.09)*	0.33 (0.11)*	0.28 (0.05)*	*0.39 (0.07)*
PLML [cm]	0.31 (0.08)	0.23 (0.05)	0.17 (0.05)*	0.17 (0.05)*	*0.19 (0.01)*
V [cm/s]	0.73 (0.14)	0.59 (0.12)	0.66 (0.11)	0.65 (0.06)	*0.63 (0.14)*
F [Hz]	1.12 (0.22)	1.03 (0.32)	1.25 (0.34)	1.33 (0.26)	*0.94 (0.12)*

The ANOVA analysis showed that statistically significant differences between the pre-surgery evaluation and the post-surgery evaluations were obtained for all parameters with the exception of the speed and frequency. More specifically, the values obtained during the post-surgery assessment were found closer to the ones obtained for the healthy leg with respect the ones obtained in pre-surgery assessment. In addition, the PL_{ML} showed statistical difference also between the values obtained during the first session after surgery and the other two. Thus, shank stability indices reveal themselves as useful prognostic factors.

The significant differences found for the t_{st}, EA, PL, PL_{AP} and PL_{ML} of the injured limb in the post-surgery assessment could allow affirming that monitoring these parameters could lead to a more quantitative evaluation of the time mandatory for the return to the competition of an injured player. In fact, it can be observed as the values obtained in the post-surgery assessment are similar to the one related to the healthy leg. Moreover, the analysis of the path length in the medio-lateral direction seems to be sensitive also to the months after the rehabilitation, suggesting that its evaluation could permit to implement a better rehabilitation program. These outcomes can be justified by the shorter duration of oscillation and to less displacements during the landing phase from the jump. It could therefore be hypothesized that the rehabilitation performed following the ACL reconstruction has positively modified the neuromotor strategies necessary to obtain a greater neuroproprioceptive control of the lower limb during the technical gesture of the landing. In addition, the increment of oscillation frequency could lead to greater joint overload, an important risk factor for ACL failure that would occur approximately within 40 milliseconds after contact with the ground of the affected lower limb [130]. In the athlete evaluated, this could indicate the need to still have to improve some specific aspects of the technical gesture of landing from the jump, in order to have a greater security of decreasing the risk of incurring new distortive traumas in the previously injured lower limb or in the contralateral one.

Analysis of new predictive indices for ACL injury in basketball on a monitored sample and case study

Introduction

The introduction of protocols instrumented with sensors as screening and prevention tools for the identification of reliable indices aimed at assessing the risk of injury in elite players is increasingly in demand [132]. In particular, the most stressed joints are the lower limb ones and the injury of the knee anterior cruciate ligament (ACL) is the most problematic and widespread.

The high risk of recurrence of injury, prolonged absence from the playing fields and the poor ability to express the same intensity and ability before the injury make it an injury feared by all athletes and operators in the sector [93–95]. ACL injury occurs particularly during the landing phase after a jump [96-100]. When the landing phase is characterized by a short duration, the athletes must attenuate the force of impact on the ground and at the same time must be able to release additional forces to perform other movements, such as changing other jumps upwards or in a other direction. It is worth noting that previous studies indicated the most likely period for ACL injury to occur 30 to 100 ms after ground contact time after jumping [101,130].

Several research have analyzed the landing phase after the jump in athletes and non-athletic subjects for evaluation, rehabilitation and performance purposes with the aim of identifying risk factors, and to provide technicians with training and intervention strategies, in people at risk, more suitable for preventing accidents [130,133,134]. Among the many technologies, video analysis is the most used methodology for identifying these risk factors. Landis *et al.* [118] performed video analysis on data collected from 180 athletes from different sports, assessed that the investigation of knee abduction at the instant of landing after the drop jump test provides useful information on the risks of ACL injury. Results also confirmed by a study by Numata *et al.* [135] who state that Knee Valgus during the landing phase of the jump is a potential risk factor for non-contact ACL injury in high school female athletes. Despite the diffusion of video analysis, the use of optoelectronic systems and force platforms had a great response in this context as they also allow for the collection of information relating to the kinematics and kinetics of the knee and ground reaction forces, which have proved to be indices linked to ACL risk of injury [103,136,137,138]. For example, Myer *et al.* [103] showed how the prevention of ACL injuries can be achieved by analyzing the kinetics of the knee at the moment of landing; in fact, they found that higher risk athletes are associated with an abnormal increase in knee abduction moment. The study by Mokhtarzadeh *et al.* [137] highlighted the antagonistic and agonistic role of gastrocnemius and soleus in ACL loading; Podrazza *et al.* [138] stressed that the relative interaction of all involved thigh and lower leg muscles during the landing phase of the single drop jump should be considered when analyzing contactless ACL injury mechanisms. However, there are many non-negligible limitations when using force platforms and optoelectronic systems. First, such systems often require a large investment due to cost. Second, analysis often takes time in subject preparation and data processing, resulting in a complicated application as a screening tool during training sessions. Over the last decade there has been a continuous increase in the appeal of wearable solutions among professionals which obviates these limitations [139].

Considering the above needs and limitations, wearable inertial sensors become prevalent [126,127,140]. Janssen *et al.* [126] used inertial sensors to acquire the athlete's kinematics at the instant of landing after a jump, finding that the valgus movement at the instant of contact with the ground can be considered a predictive factor; similar work has been proposed by Dowling *et al.* [127], suggesting that analysis of the knee flexion angle after a jump is important to obtain useful information on knee stability. Taborri *et al.* [140] showed how data collected by an inertial sensor when performing single-leg jumps and single-leg squats are useful for fueling machine learning algorithms capable of identifying athletes at highest risk of injury. It is important to note that the reliability of all the indices proposed in the previous studies has not yet been tested, even if the metrological characteristic of reliability is recognized as fundamental for introducing objective indices into clinical routine [140]. Furthermore, to the best of the authors' knowledge, all previous studies have focused on analyzing data relating to a single jump the instant the subject touched the ground, neglecting both the entire movement during the stabilization period after contact with the floor and the effects induced by repeated jumps.

However, suboptimal landing has been shown to cause 50% of acute knee injuries, thus indicating how important proper landing and stabilization techniques are; in fact, an optimal landing technique involves a soft landing with the muscular system always active and in control, the absorption of energy is therefore more efficient and a reduction of the load on the lower limbs occurs [141]. Furthermore, previous studies have not considered other technical gestures independently of the jump nor parameters related to the stability of the leg, with the exception of a preliminary study proposed by the same authors of this work [142].

Among others, in basketball there is a high rate of ACL injuries due to continuous contact between players and the need to develop high strengths in short spaces and times [93-95]. Furthermore, women have shown a greater predisposition to ACL injury than men with a 2 to 8 times higher level of injury due to anatomical, physiological and biomechanical factors [99-101]. From this perspective, the objectives of the study are twofold. Firstly, an experimental protocol that can be used as a screening tool during training sessions based on the execution of repeated vertical monopodalic jumps and single leg squats is presented. Secondly, we want to test the reliability of the synthetic indices relating to leg stability, load absorption and leg mobility, which can be considered both as predictive risk factors and as monitoring factors for the assessment of time to return to the game after the reconstruction of the ACL. As a further objective, the proposed experimental protocol and analysis methodology are applied to a case study involving a basketball player who suffered an ACL injury during the observational study.

Materials & Methods

Participants

Thirteen female athletes of the Italian Under 14 national basketball team (height = 171.4 ± 7.6 cm, body mass 65.4 ± 6.3 kg, age = 13 ± 1 years) participated in a fourteen-month observational study. One of the athletes, named hereinafter as athlete A, is present as case study, since she suffered an ACL injury during an international basketball match, less than two weeks after the first acquisition session. Specifically, medical staff reported an ACL rupture of the left knee caused by an incorrect landing phase after a monopodalic jump with a pivot-shift mechanism.

The athlete underwent to ACL reconstruction and the return-to-play has been authorized after six months of rehabilitation.

The remaining twelve athletes were included in an experimental protocol to both evaluate the reliability of the proposed synthetic indices and create reference values as control group (CG). Athletes were included if they were in good health and without serious injuries at least in the last three years of activity, where they trained regularly for five days a week.

The parents, or tutors, of each girl were asked to accept informed consent through a written document following a meeting to present the methods and objectives of the study. The experimental protocol complied with the 1964 Helsinki Declaration.

Experimental Setup

Two devices were used for the data acquisition during the experimental protocol both considering the reliability analysis and the case study: GyKo and Optogait.

GyKo (Microgate S.r.l., Italy) is a Magneto-Inertial Measurements Units (MIMUs) comprises 3D linear accelerometers, gyroscopes and magnetic sensors (± 16 g, ± 2000°/s and ± 4800 µT of full-range scale, respectively), measuring 3D linear acceleration, angular velocity and magnetic field vector. The sample frequency was set at 1000 Hz, which guarantees the appropriate acquisition of high dynamic tasks as the jumps. The sensor was fixed using the semi-elastic belt supplied and the specific magnetic support for the device to reduce movement artifacts during tests. It was fixed at the same height from the floor by the same operator to avoid errors in positioning. The same height also guarantees the possibility to perform comparison of stability indices related to players with different height. Data acquired by the sensor was transmitted via Bluetooth to a personal computer and saved with the Optogait software (version 1.12.1.0). The GyKo inertial sensor is commonly used for the evaluation of motor activities such as jumping tests [30,143], muscle strength tests [31] and balance tests [143,32]. Optogait is an optoelectronic device (Optogait, Microgate S.r.l, Italy, 2010) consisting in transmitting-receiving bars (length of 1 m) positioned above the ground. Each bar is equipped with ninety-six LED diodes and it was synchronously associated to the GyKo in order to estimate the time of flight (FT) and the contact time (CT) during jump tests. Four Optogait bars were placed on the ground to create a square of 2 x 2 m2. The Optogait system is mainly used in the analysis of human movements, especially for gait [26,27] and jump gesture analyses [143]. Finally, two synchronized cameras (Logitech C920 HD) were used to acquire both sagittal and frontal plane and they placed at about 2.5 m from the participant.

Experimental Protocol

Test sessions were held at the Istituto di Medicina e Scienza dello Sport (CONI) of Rome. Before each session, a 10-minute warm-up was performed by each athlete with a focus on the lower limb joints. Specifically, mobility exercises and cyclo-ergometer were required to each participant. The experimental protocol consisted in two tasks: monopodalic countermovement jump (mCMJ) and single-leg squats (SLS). At the beginning of each test, the subject was asked to remain stationary in standing position asking players to keep for 10 s the upright position with the arm at their side and the foot shoulder-width apart and parallel to record data for the calibration of the sensors. Successively, the subjects were asked to execute task with both lower limbs. Each player firstly performed the tasks with the right leg and after with the left one.

Monopodalic countermovement jump – mCMJ

The mCMJ consists in five consecutive monolateral vertical jumps with arms free to move. The athlete was asked to reach the single-leg starting position with the foot shoulder-width apart and, after the start signal, to perform five maximal single-leg countermovement jumps (Figure 12). In the countermovement jumps the subject started from a standing position with their feet shoulder-width apart and their arms free. Then performed a downward movement, which is immediately followed by a concentric phase. For this task, both GyKo and optoelectronic bars were used.

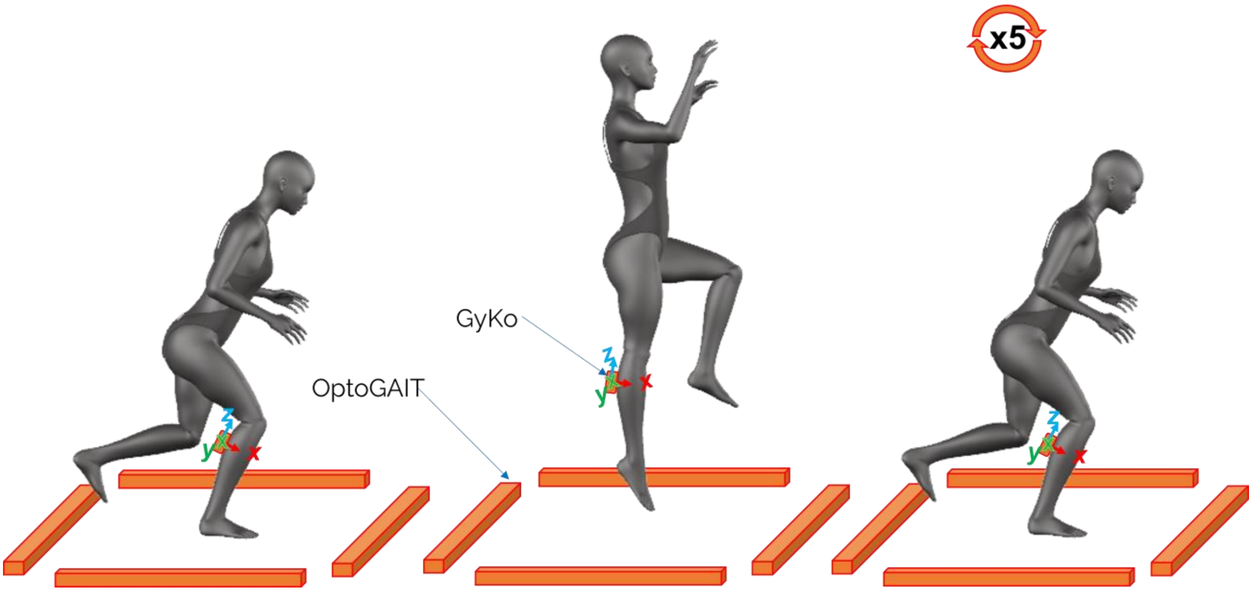


Figure 12. Monopodalic countermovement jump: Sensor positioning and sequence of movement.

Single-leg squats – SLS

The SLS is a squat movement performed on only one leg. The athlete started from a standing bipodal position, then pass on one leg and the other leg was lifted off the ground in front of the body. After having reached this position, subject was asked to perform five consecutive squats with the stance limb. Subject was instructed to maintain the arms with the hands on the hips. The subject was asked to descend as much as possible while maintaining position and balance [144] (Figure 13). For this task only the GyKo was used; in fact the task does not deal with contact and no contact period and the measurements of the OptoGait is not necessary.

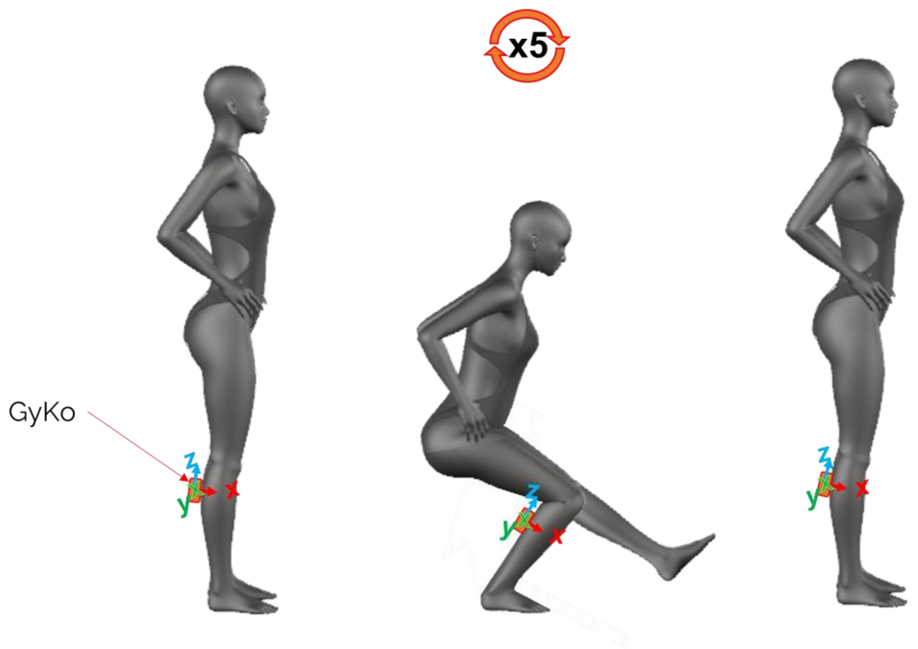


Figure 13. Single Leg Squat: Sensor positioning and sequence of movement.

All participants were able to complete the entire protocol that lasted approximatively 20 minutes per athlete, including the sensorization phase.

Athlete A completed four sessions: one before the ACL injury and the following three sessions were carried out at a distance of 6, 9 and 12 months from the operation; the average days between two consecutive sessions was 86 ± 5 days. This data was analyzed for the case study and the sessions are named, hereinafter, as PRE, POST1, POST2 and POST3. Three sessions were, instead, carried out by the CG at a distance of 3 months from each other; the average days between two consecutive sessions was 87 ± 4 days; the acquired data was used for the reliability analysis and to create the reference values.

Data Analysis

As regards the GyKo inertial sensor, the re-alignment of its axes with the absolute reference system has been carried out by processing the data acquired during the static calibration for both tasks. The orientation of the sensor was computed by combining linear accelerations and angular velocities through a fusion algorithm based on the Mahony filter [43]. Three sets of parameters were successively calculated in order to evaluate the athletes' performance in terms of leg stability, load absorption capability and leg mobility.

Leg stability

As concerns the leg stability, the parameters were calculated considering the orientation of the vertical axis ($\vec{z}$) of the sensor derived from the combination of the acceleration and angular velocity signals. The stability of the leg was analysed considering the intersection between the axis related to the longest side of the sensor and the horizontal plane, corresponded to the floor, placed at 1 cm from the inertial system. The path covered by the intersection point was then analysed using parameters usually used in posturographic analysis by the equations reported in [39]:

- Path Length (PL), which is total length of the path in the plane.

- Path Length in antero-posterior direction (PL_{AP}).
- Path Length in medio-lateral direction (PL_{ML}).
- Ellipse Area (EA), which is the minimum area of the bivariate confidence ellipse that contains at least 99% of the path.

Specifically, PL was computed by the sum of the distances between two consecutive points of the path covered by the intersection point (Equation 1).

$$PL = \sum_{n=0}^{N-1} [(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2]^{1/2} \quad (1)$$

where N represents the number of points of the path. The PL was also evaluated considering the antero-posterior (PL_{AP}) and medio-lateral (PL_{ML}) components one at a time. The EA was instead computed as in the Equation 2.

$$EA = 2\pi F_{.05[2,N-2]} [s_{AP}^2 s_{ML}^2 - s_{APML}^2]^{1/2} \quad (2)$$

where $F_{.05[2,N-2]}$ is the *F* statistic at a 95% confidence level for a bivariate distribution with *N* points. s_{AP}^2 and s_{ML}^2 are the variance of the AP and ML, and s_{APML}^2 is the covariance.

A schematic example of PL and EA is reported in Figure 14.

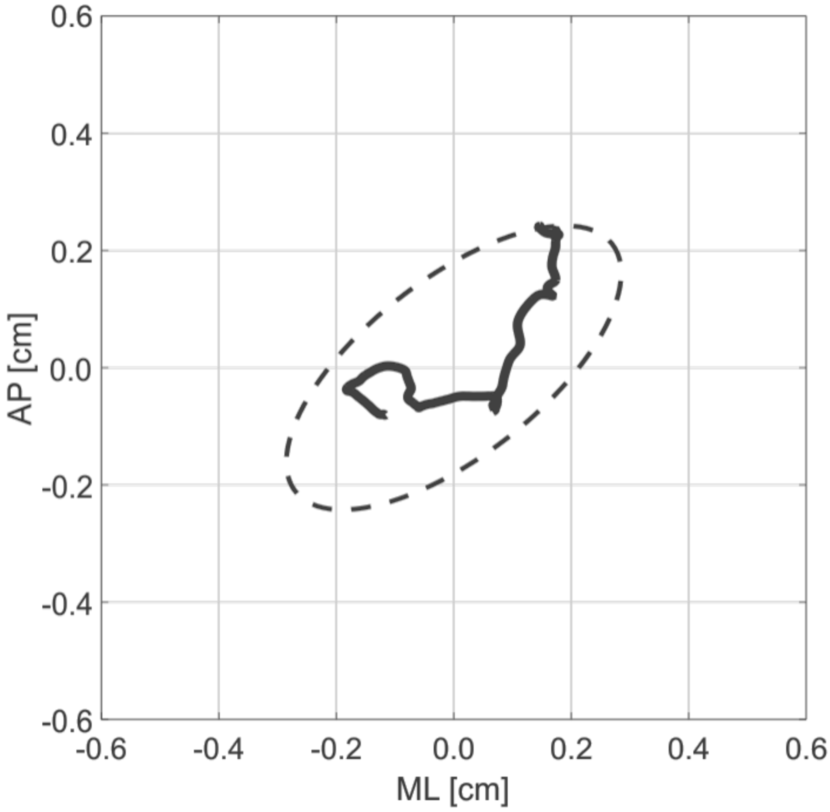


Figure 14. Example of path length (bold blue line) and confidence ellipse (dotted blue line) in the AP-ML plane.

For all the reported parameters, greater is the value, higher is the instability of the shank after the jump landing; in fact, greater values of EA and PL indicate an increase in the displacement [44]. We have selected such indices since it has already been demonstrated that the increase of instability immediately after jump landing can be considered as one of the main causes of ACL injury [130]. These parameters were computed for both tasks. Considering mCMJ, these parameters were normalized for the stabilization time (T_s), which represents the time immediately after the landing phase that guarantees the stabilization of the leg. Specifically, Ts was defined as the temporal distance between the initial contact time (CT) with the ground and the instant in which the leg can be considered as stable, corresponding to the first minimum of the absolute value of the shank's angular velocity, named as ω_{min} (Figure 15). The CT_i was detected by considering the on/off status of the led in optoelectronic bars, which also allowed to computed the duration of the flight time ΔFT; whereas the ω_{min} was automatically computed within the period of the contact time ΔCT.

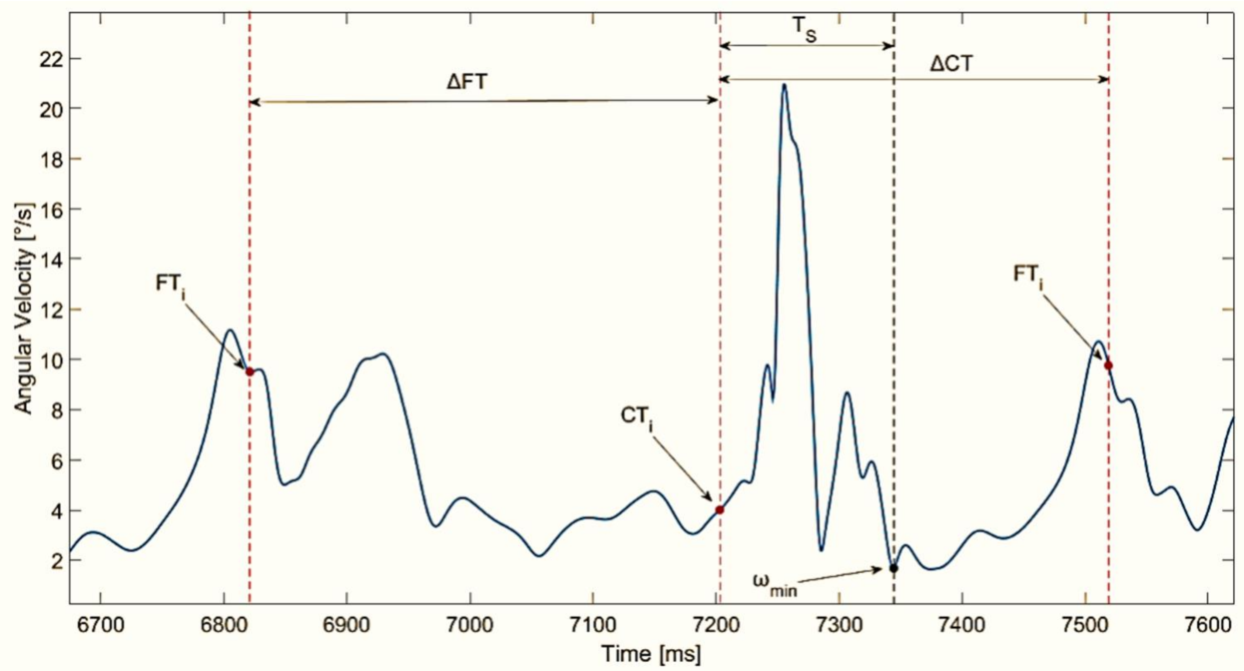


Figure 15. Identification of the stabilization time (Ts). ΔCT is the Contact Time, ΔFT is the Flight Time. CT_i and FT_i represent the initial contact time and the initial flight time phase, respectively.

Regarding the SLS, the leg stability parameters were normalized for the descending phase (T_{DP}), which was the only analysed phase since it was characterized by a greater load to the knee joint [144]. To identify the initial instant of DP (DP_i), the average value of the standard deviation (SD) of the module of the three angles on the X, Y and Z axes was firstly calculated in the first 2 s of each test, individually per each subject. Then, the initial instant was automatically identified by an ad-hoc implemented algorithm as the one in which the average value of SD was overcome five times. The end point (DP_e) corresponds to the maximum value reached by the angle around the Y axis (θ_{ymax}), i.e. the one corresponding to the knee flexion (Figure 16), gathered from the GyKo data.

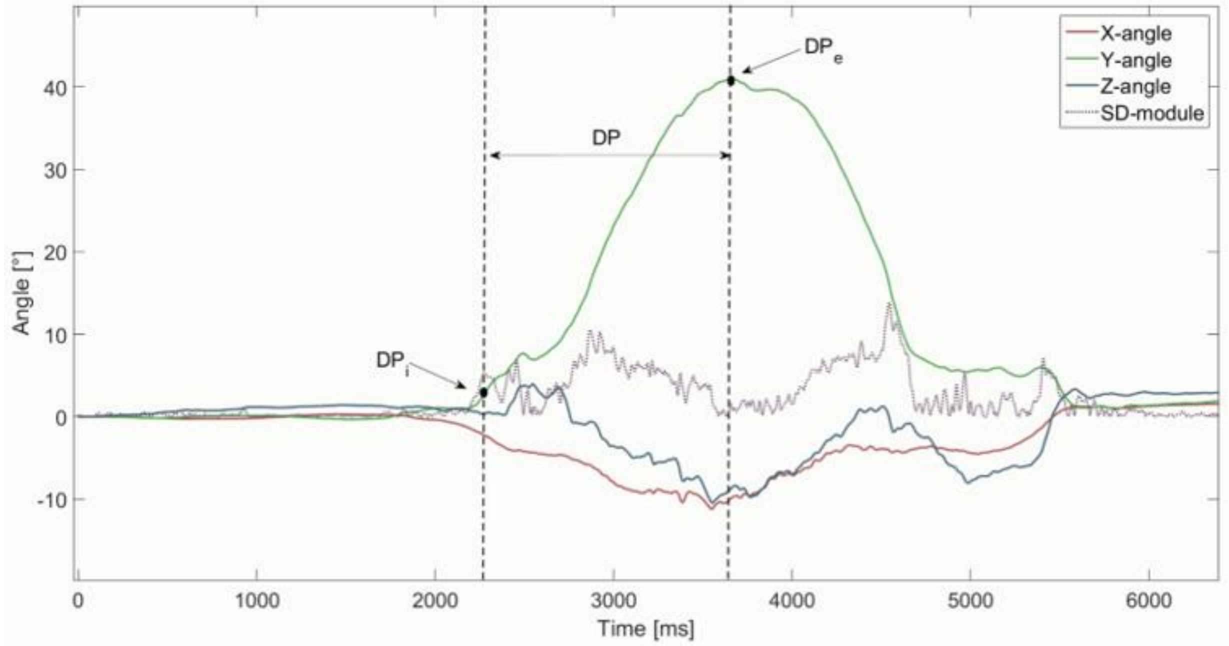


Figure 16. Identification of the Descending Phase (DP). DP_i is the initial instant of the DP and the DP_e is the end of the DP.

Load absorption capability

The analysis of the capability to absorb the load after jump was conducted only considering data gathered during mCMJ. Specifically, shank linear acceleration was firstly divided into two components, which were the vertical acceleration and the acceleration on the horizontal plane xy defined as the module of the two acceleration components x and y. Then, the Root Mean Squares were calculated for both components, vertical (RMS_z) and along the plane xy (RMS_{xy}), both expressed in m/s^2. As for the stability indices, these parameters were finally normalized by dividing them by the jump duration. Greater value of the RMS indicates the poor capability of load absorption [145].

Leg mobility

The analysis of the leg mobility was conducted only considering data gathered during SLS. Specifically, the knee mobility was associated with the above-mentioned θymax. In particular, lower is the value of θ_{ymax}, lower is the mobility [146].

Reliabilty Analysis

Reliability analysis was conducted by considering the data acquired during the three sessions performed by the CG to find the most reliable indices capable to evaluate changes in the subject affected by ACL injury. For each session, the average across the five jumps and squats for each parameter was calculated and then the Inter-Class Correlation Coefficient (ICC) among the three sessions based on absolute-agreement and 2-way mixed-effects model was computed. Due to the symmetry between right and left side, the analysis was only performed on the dominant leg, identified as the one used to kick a ball. ICC analysis allowed to quantify the inter-day reliability by understanding the effects induced by both the re-placement of the sensor on the shank and the daily changes of individual pattern in performing the technical gestures. Level of reliability was then classified according to the following ranges of ICC values: (i) poor reliability if ICC ranged from 0.00 to 0.39; (ii) fair reliability if ICC ranged from 0.40 to 0.59; (iii) good reliability if ICC ranged from 0.60 to 0.74; and (iv) excellent reliability if ICC ranged from 0.75 to 0.99, as reported in [38]. The indices that showed at least a good reliability, *i.e.* ICC values equal or greater than 0.60, were subsequently used for the case study.

Case Study Analysis

Considering only the indices that passed the reliability analysis, the average values across all the participants in the control group were evaluated to collect the reference values. Data gathered from the case study were processed and analysed considering the PRE, POST1, POST2 and POST3 sessions, individually.

In order to identify the presence of statistical difference between data related to PRE and CG, a t-test was performed individually for each parameter. Any difference can lead to the identification of possible predictive factors.

By only considering the parameters that were significant in the t-test in the PRE session, we performed a one-way ANOVA in order to identify the presence of statistical differences among the experimental sessions of the case study. Tests were conducted individually for each parameter. When statistical differences were found, a Bonferroni post-hoc analysis for multiple comparison was applied. Finally, each parameter related to each POST session was compared with the one associated with CG by performing a t-test in order to assess the effectiveness of the rehabilitation program on the injured leg and to identify indices that are able to monitor the return-to-play time. The analyses were performed only on the injured leg; for the difference between injured and no-injured leg please refer to the preliminary study reported in [142].

For all the statistical analyses, the significance level was set at 0.05.

Results

Reliability Analysis

The ICC values for the mCMJ and SLS are reported in the Figure 17.

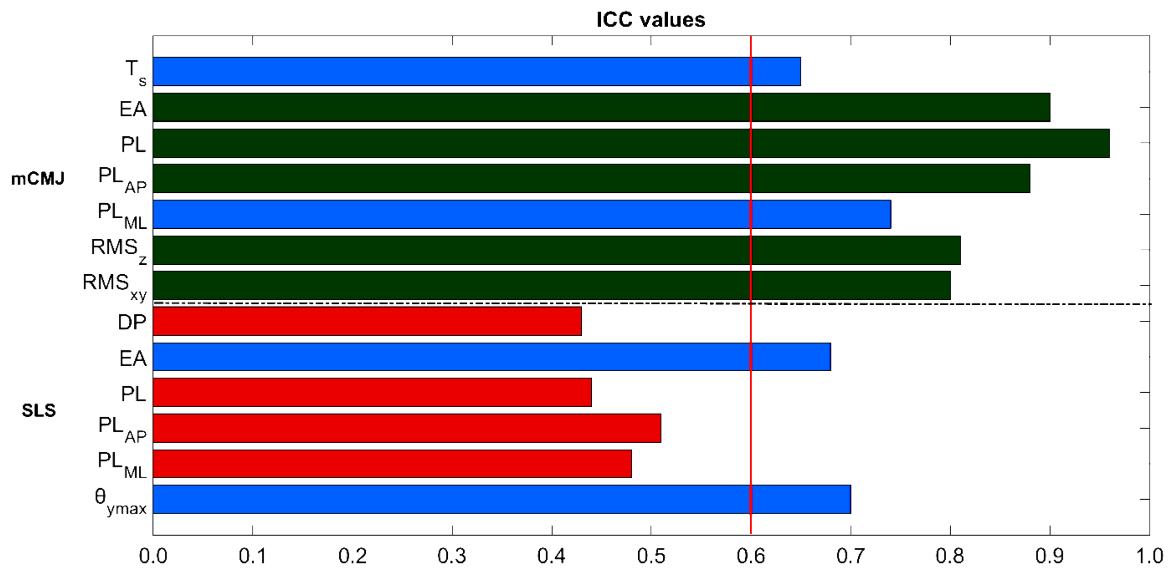


Figure 17. ICC values for all the computed parameters for both mCMJ and SLS task. Red, blue and green bars indicate fair, good and excellent reliability, respectively. The red vertical line represents the set threshold for acceptability, which is 0.60. The dotted black line separates the parameters related to the two motion tasks.

By analyzing mCMJ results, all the parameters reached an ICC value greater than the acceptability threshold set at 0.60. Specifically, all parameters achieved results ranging from good to excellent reliability, with the maximum value obtained for the PL, i.e. equal to 0.96, and the minimum for the T_s (0.65). By moving to the SLST, only the EA and θ_{ymax} can be considered as reliable index since they fell into the good reliability range, with value of 0.66 and 0.70, respectively. Conversely, all the other parameters showed ICC values always lower than 0.51 and they have not been considered for the case study due to the fair reliability.

Case Study Analysis

The results related to the comparison between control group and athlete A for the PRE session are reported in Table 10 for both mCMJ and SLS. As already reported, the only parameters considered were the ones that showed an ICC ≥ 0.6.

Table 10 - Mean (SD) of the parameters related to the mCMJ and SLS task for the PRE session for both control group (CG) and injured athlete (Athlete A). * indicates statistical differences with respect CG.

	mCMJ							SLST	
	T_s [s]	**EA [cm²/s]**	**PL [cm/s]**	**PL_{AP} [cm/s]**	**PL_{ML} [cm/s]**	**RMS_z [m/s³]**	**RMS_{xy} [m/s³]**	**EA [cm²/s]**	**θ_{ymax} [°]**
CG	*0.24 (0.06)*	*0.42 (0.12)*	*1.08 (0.15)**	*0.75 (0.16)**	*0.68 (0.07)*	*57.21 (7.99)**	*48.69 (11.40)**	*0.33 (0.11)*	*28.5 (2.6)**
Athlete A	0.22 (0.03)	0.30 (0.09)	1.56 (0.20)*	1.35 (0.20)*	0.58 (0.12)	81.73 (10.18)*	78.40 (14.15)*	0.32 (0.10)	21.8 (1.5)*

By analyzing the results, PL, PL_{AP}, RMS_z and RMS_{xy} related to the mCMJ task and the θ_{ymax} related to the SLS were statistically different between the athlete A and the control group (*p-value* ranged from <0.01 to 0.02). More specifically, greater values extracted from the SLJP were obtained for the athlete A compared to CG, as well as a lower θ_{ymax} in the SLS. Conversely, no differences were found for the Ts and for the EA computed in both tasks.

Figure 18 shows the values for the selected indices related to the case study considering all the experimental sessions, as well as the statistical difference.

By analysing the results, ANOVA tests exhibited statistical differences for all the indices. Considering the leg stability indices, PRE value was found different from all the three POST sessions for both PL and PLAP (*p-value* always <0.01). Conversely, no differences among the three POST sessions were found. Analysing the load absorption capability, POST1 values were statistically different from both the PRE and the last two POST sessions for both RMS_z and RMS_{xy} (*p-value* ranging from <0.01 to 0.03). For the same parameters, no differences were found for PRE and the last two POST sessions. Furthermore, the leg mobility showed the same behaviour of the load absorption parameter.

Finally, the results of the comparisons between the POST and CG are depicted in Table 11. Considering the leg stability, no differences with respect to the CG were found for all the three POST sessions. By moving to the indices associated with the load absorption, both RMS_z and RMS_{xy} decreased in the POST1 and no differences were found with respect to the CG.

Conversely, both parameters exhibited an increment of the mean value in the POST2 and POST3, showing differences with respect to the CG (p<0.01). Similar trend was found for θ_{ymax}.

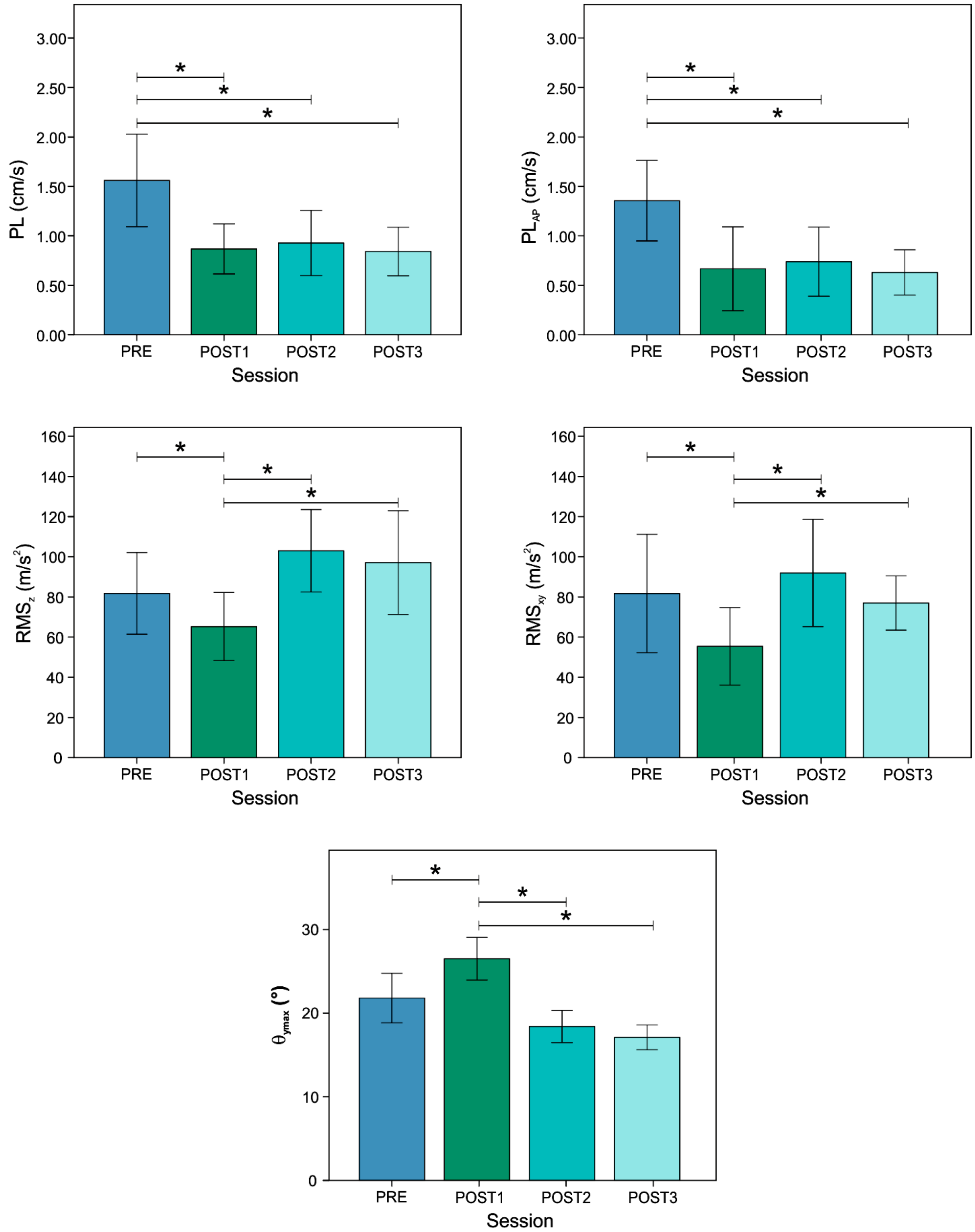


Figure 18. Mean and standard deviation for each parameter related to each session of the Athlete A. * indicates statistical difference between sessions.

Table 11 - Mean (SD) of the parameters related to the selected parameters for each POST session of the injured athlete (Athlete A) and the CG. * indicates statistical differences with respect CG.

	PL [cm/s]	**PL$_{AP}$ [cm/s]**	**RMS$_z$ [m/s^3]**	**RMS$_{xy}$ [m/s^3]**	**θ_{ymax} [°]**

CG	*1.08 (0.15)*	*0.75 (0.16)*	*57.21 (7.99)*	*48.69 (11.40)*	*28.5 (2.6)*
Athlete A POST1	0.87 (0.13)	0.67 (0.21)	65.20 (8.41)	53.24 (9.20)	26.5 (1.3)
Athlete A POST2	0.93 (0.16)	0.74 (0.17)	103.00* (10.20)	88.25* (12.81)	18.4* (0.9)
Athlete A POST3	0.84 (0.12)	0.63 (0.11)	97.11* (12.86)	73.88* (6.47)	17.1* (0.7)

Discussions

Through the aim to investigate the identification of quantitative measurements able to identify ACL injury risk and to monitor the time needed for the return-to-play of injured athletes, we performed a reliability analysis on parameters related to the leg stability, load absorption and leg mobility during monopodalic jump and single leg squat. Then, we applied this innovative methodology to compare a control group of basketball players with an athlete who occurred in ACL rupture during an observational study.

Are the proposed indices reliable to evaluate leg stability, leg mobility and load absorption capability?

Results related to the reliability permit to assume that the proposed indices show a good-to-excellent reliability, considering all the parameters computed for the monopodalic jump tests. The reported inter-session reliability permits to consider negligible the effects of both the sensor re-placement on the body segment and the intra subject variability of motor tasks performed in different days. The negligible effects of the sensor re-placement can be ascribed to the application of the re-alignment operation as the first data processing step by using data acquired during the static calibration, as well to the skilled operator performing the sensor placement. This finding permits to enlarge the high reliability, already showed in literature, of the vertical bipodalic jumps respect to the monopodalic ones [147]. Conversely, results recommend attention when considering parameters related to the single leg squat analysis, since only the angle and the ellipse area reached a good reliability. Since the sensor re-placement and axes alignment procedure have been performed both for monopodalic jump and leg squat analysis, we can speculate that the poor reliability of the squat indices is mainly due to the intra-subject variability in performing such task considering several days. This speculation confirmed the findings assessed by Van Der Straaten *et al.* [144], who showed as the kinematics related to the single leg squat test, especially regarding the knee and the ankle joint, was poor. One of the main causes that leads to the movement variability could be the absence of a clear endpoint for the knee flexion, since athletes were instructed to reach a maximum knee flexion angle without losing balance [144]. In addition, in young and healthy population it has been already demonstrated that the achievement of a successful SLS can be reached by a combination of multiple movement strategies, also known as movement redundancy [148].

As a conclusion, the here proposed parameters to analyse monopodalic jumps can be considered robust to both sensor re-placement and typical intra-day variability when analysing jump tests; conversely the variability of single leg squat movement influence the reliability outcomes. Finally, for all the indices that range from good to excellent reliability we can affirm that any potential differences occurred when comparing control group and injured athletes can be ascribed to the ACL injury risk.

Should the reliable indices be monitored to identify athlete at higher injury risk?

The analysis of the results obtained when comparing control group with the data gathered from the athlete who occurred in the ACL injury after the PRE session could highlight useful synthetic indices capable to discriminate a higher injury risk. The statistically higher values of the path length, both in the plane and in antero-posterior direction, related to the athlete A could be ascribed to an increment of the instability of the leg at higher risk when it is landing after a jump. These outcomes are in line with previous studies, in which the instability during jump landing or turning movements has been depicted as one of the main causes of ACL injury [130,131]. Conversely, the absence of statistical differences of the path length in medio-lateral direction can be justified by the role of the ACL, which is mainly involved in the stabilization of the tibia, or more specifically of the knee, in the antero-posterior direction [149]. The higher values of the root mean square of the acceleration related to the injured athlete demonstrate a different load absorption strategy, suggesting an ineffective technique of load dissipation during landing. This outcome can lead to an increment of the ACL injury risk, as also reported by [150]. Finally, the leg mobility obtained during single leg squat test seems to be a further discriminating parameter to evaluate athletes with an ACL deficiency, confirming the outcomes reported by Markström *et al.* [149], who found a reduction of limb mobility during motor tasks in athlete at higher injury risk. The found lower value of θ_{ymax} can also lead to the inability of the hamstrings to restrain the force place on the ACL, causing potential risk of injury, as reported in [151]. To summarize, the results of the comparison between PRE session and CG allows us to encourage the analysis of the leg stability after monopodalic jump test, especially if considering the path length and the RMS of the accelerations, and the evaluation of the leg mobility during single leg squat test as a useful clinical tool to assess athletes at higher risk of anterior cruciate ligament injury. Thus, a periodic assessment of the leg stability and load absorption, as well as the joint mobility should be adopted by athletic trainers to early predict injury events and to implement specific training programs during coaching to reduce the risk.

The outcomes obtained when comparing the POST sessions with the control group have to be taken into account in order to evaluate the effects of the rehabilitation program and to identify the correct return-to-play time. By analyzing the results related to the POST1, we can assess that six months are sufficient to a complete functional recovery of the leg, as demonstrated by the absence of statistical differences between athlete A and the control group. These findings confirm the studies already proposed in literature that indicated six months as the right period to wait for the return to competition [152]. Several studies demonstrated a high rate of second injury in the following two years after the first trauma [153,154]. In this direction, our results showed a significant deterioration of motor performance in terms of load absorption capability and leg mobility nine and twelve months after surgery; conversely a physiological behavior is maintained for the leg stability. These outcomes suggest both the necessity to implement specific training programs for athletes with ACL deficiency mainly addressed to the leg mobility and the capability of load absorption, and the usefulness of monitoring these parameters in order to early predict the occurrence of new ACL injury.

Assessing the risk of ACL injuries in basketball players: a new methodology through a machine learning approach

Introduction

One of the most popular team sports in the world is basketball with over 450 million amateur and professional players [132]. During training and competitions, athletes must perform very dynamic movements, which often also require physical contact between the players. Furthermore, basketball is a vertical sport and the demand for jumping and landing is two to three times higher than in other team games, such as football, volleyball and rugby [155]. These aspects are the main cause of a high incidence of injuries among basketball players and the knee joint has been shown to be the most commonly stressed and injured body area [156]. Among others, anterior cruciate ligament (ACL) rupture may be considered the most debilitating injury, often leading to long periods of rest before returning to play [150]. Also, along with ankle sprains, ACL injury has the main incidence in basketball players; for example, 16% of female athletes may experience an ACL injury during their career and it is worth noting that the risk of ACL rupture in female players is up to eight times higher than in male players [157]. The treatment path of the ACL injury always requires reconstructive surgery, a consequent absence from the playing field for at least six months, and a clinical rehabilitation program that is sometimes not sufficient to recover the complete functionality of the knee and the capacity of the athlete before injury [155]. Several studies have been conducted to understand the main causes of risk and an increase in the occurrence of injuries is associated with a combination of anatomical, physiological and biomechanical factors [99-101].

With this in mind, with the aim of proposing dedicated programs capable of reducing the incidence of injuries, various methodologies have already been validated to provide useful information for identifying athletes at greater risk of injury [158-160]. In this context, optoelectronic systems combined with force platforms still represent the gold standard for having accurate and repeatable measurements of complex and specific movements, such as cross tests, pivoting jumps, counter-movement jumps [161-163]. In addition, a great help was provided by the video analysis which showed its abilities in identifying the risk of ACL injuries that do not require qualified operators given the simplified operations and offering the possibility to record data during sporting activity with low-cost devices [164,165]. The Landing Error Scoring System (LESS) develops from the video analysis approach and has been implemented and validated as a predictive methodology for knee injury [166,167]. The LESS is a clinical screening tool capable of identifying potential ACL lesions consisting of the analysis of biomechanical factors based on three jumping tasks [167]. However, its validity is still under discussion, the major limitations have been highlighted mainly due to the subjectivity of the video analysis which leads to a low inter-operator reliability of the procedure [168-170]. In recent years wearable solutions have been proposed to perform experimental tests also directly on the playing field, overcoming the intrinsic limit of optoelectronic systems [142,171].

Based on the above existing methodologies and their limitations, as well as the benefits of artificial intelligence (AI), the application of machine learning algorithms appears to be a promising approach to both predicting and diagnosing ACL injury [172-178]. Focusing on the diagnostic aspects, Lao *et al.* provided an overview of the application of AI to magnetic resonance imaging (MRI) capable of detecting ACL lesion [175], among others the work proposed by Mazlan *et al.* shown that the support vector machines were able to classify up to 100% of three different ACL lesions, which were normal, partial and crucial [172]. Similar results were obtained by applying the convolutional neural network to coronal magnetic resonance imaging, achieving an accuracy of 96% in the diagnosis of ACL [173]. Considering instead the use of AI as a predictive tool, Jauhieinen and colleagues demonstrated how the random forest was able to detect the most predictive biomechanical factors, which were mostly related to the kinematics and kinetics of the knee joint, during the vertical jump tests performed by 314 basketball and football players [176]. In addition, the difficulty in predicting future injuries was assessed, also confirmed by the low value of the area under the receiver operator curve below 0.70 both for the random forest and for the logistic regression. Oliver *et al.* achieved similar results by analyzing knee kinematics data, which tested 355 football players during single-leg countermovement jump and single-leg jump for distance testing [177]. Furthermore, Tedesco *et al.* demonstrated that the gradient boosting algorithm, fed with data related to acceleration and leg stability, is able to discriminate between healthy players and subjects with post-ACL injury with an accuracy close to 82%. Therefore, this approach can be used as a useful monitoring tool for identifying adequate time to return to sport [178].

However, it is important to underline that although the promising utility of AI in providing automatic information both for diagnosing and predicting ACL lesions is evident, the results obtained are not completely satisfactory for proposing the use of such methodologies in the daily routine. Furthermore, to the best of the authors' knowledge, no study has evaluated either the correlation between the predictive tool actually used, such as the LESS score, and the use of the AI approach, or the feasibility of using data relating to the stability and load of the leg absorption capacity to power machine learning algorithms. Therefore, this paper aims to understand the feasibility of machine learning algorithms to rank basketball players at highest risk for ACL injury using the LESS score as the algorithm training supervisor. More specifically, an observational study was conducted on female basketball players under 14 while performing single-leg vertical jump and single-leg squat tests and compared several machine learning algorithms powered by characteristics extracted from inertial data regarding stability, mobility and load capacity of the legs. The results of this study could offer the possibility of using AI for automatic identification of athletes at greatest risk, allowing for the implementation of personalized training programs aimed at injury prevention.

Materials & Methods

Participants

Thirty-nine basketball players belonging to the female Under 14 Italian team (height = 170.5 ± 6.3 cm, body mass 62.9 ± 4.9 kg, age = 13 ± 1 years) were involved in the experimental protocol. Athletes were included in the study if: (i) they did not suffer from severe injuries in the last three years, (ii) they trained at least five times per week; and (iii) their parents, or tutor, accepted the written informed consent. Any injuries at knee level, both severe and moderate, caused the exclusion from the test. All the tests in the experimental protocol have been decided with coach and athletic trainer and they met the criteria required by the Declaration of Helsinki.

Experimental Setup

The experimental setup consisted in three sensor systems: a magneto inertial measurement unit - MIMU (GyKo, Microgate S.r.l., Italy), optoelectronic bars (Optogait, Microgate S.r.l, Italy, 2010) and cameras. The MIMU is composed of 3D linear accelerometers, gyroscopes and magnetometers, allowing to measure linear acceleration, angular velocity and magnetic field vector, with a full scale of ± 16 g, ± 2000°/s and ± 4800 μT, respectively. The sensor was placed on the shank using an elastic belt, appropriately designed to reduce the movement artifacts. Four optoelectronic bars were used in order to create a square field of measure of 2 x 2 m^2; each bar consisted in 96 LED diodes, which allow to estimate both the flight and contact time during jumps. Finally, two cameras (Logitech C920 HD) were used to acquire both sagittal and frontal plane and placed at 2 m from the participant.

Experimental Protocol

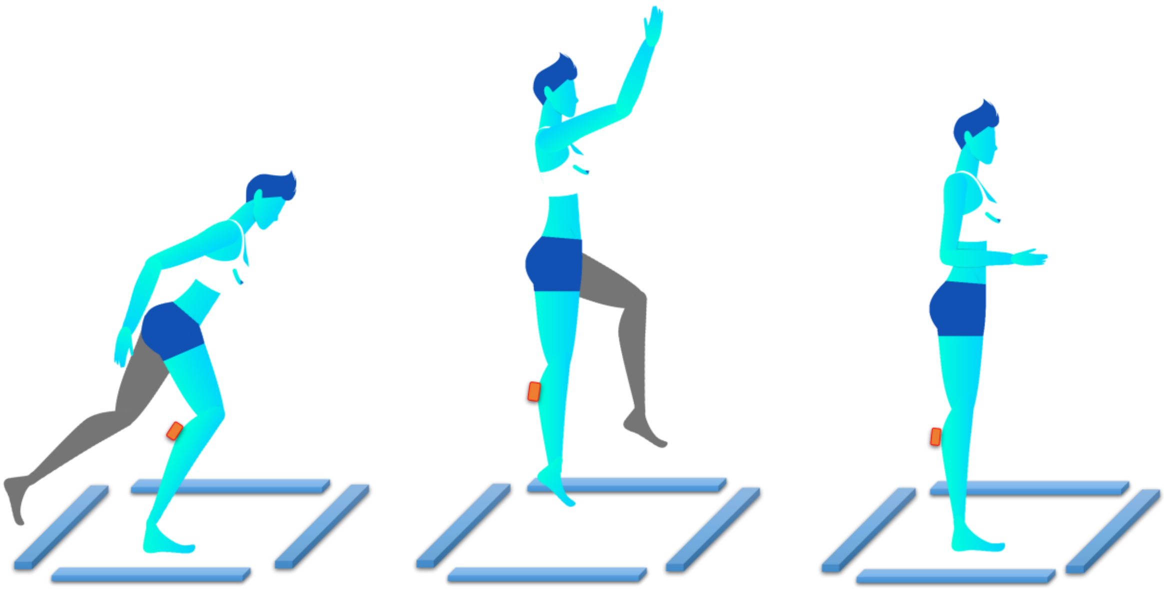
The experimental protocol consisted in three phases: warm-up, clinical assessment and sensor-based assessment.

As regard the first phase, a 10-minute warm-up for the lower limb joint was conducted, including standard stretching exercises for lower limb mobility and five minutes of biking.

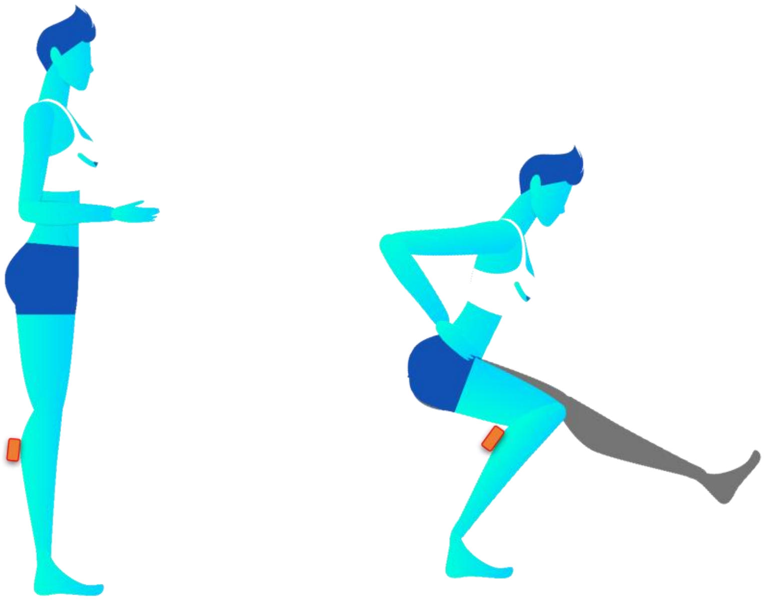
Successively, the clinical assessment phase was performed in order to compute the LESS score. Each athlete was asked to perform a jump-landing task that involved both vertical and horizontal movements; in particular, they jumped forward from a 30 cm box and after the landing they immediately performed a maximum vertical jump. The jump-landing task was repeated three times. During this phase data for successive analyses were gathered from the two cameras.

Finally, the sensor-based assessment was composed of two motion tasks. Firstly, each participant was asked to perform five consecutive monopodalic countermovement jumps (mCMJ) [145], receiving the instruction to complete this movement sequence (Figure 19a): (i) reach a single-leg starting position with the foot shoulder-width apart; (ii) perform a downward movement; (iii) immediately execute a concentric phase; and, (iv) repeat point (ii) and (iii) for five times. During all movements the arms were free to move. The second task consisted in a single-leg squat (SLS), in which participant had to perform a squat on a single leg maintaining the arm with the hands on the hip and extending the other leg in front of the body [144], as in Figure 19b. Five repetitions of SLS was performed. Both GyKo and optoelectronic bars was used during the first task, whereas only the GyKo was used for gathering data during the second one.

All the tests were performed with the dominant leg, which was selected as the one used to kick a ball [38]. The entire protocol lasted 20 minutes per athlete, also considering the time for the sensorization and the time need for a static acquisition in upright position before each motion task.



(a)



(b)

Figure 19. (a) movement sequence related to the monopodalic countermovement jump and (b) movement sequence related to the single leg squat. The four grey bars on the floor represent the optoelectronic bars, instead the gray box on the subject's shank the MIMU.

Data Analysis

Clinical assessment phase: LESS score

Data acquired during the jump-landing task were analyzed through a video analysis performed by a skilled operator. The feet, ankle, knee, hip, trunk, shoulder, neck and head posture was assessed through the video and the LESS score was obtained by analyzing the landing technique error based on 17-items questionnaire showed in the Table 12, as proposed by Padua *et al* [167].

Table 12 – 17-items for the evaluation of the LESS score

Item	Possible score
1. Knee flexion angle at initial contact > 30°	0 = yes 1= no
2. Knee valgus at initial contact, knees over mid-foot	0 = yes 1= no
3. Trunk flexion angle at contact	0 = trunk is flexed 1 =not flexed
4. Lateral trunk flexion at contact	0 = trunk is vertical 1 = not vertical
5. Ankle plantar flexion at contact	0 = toe to heel 1 = no
6. Foot position at initial contact, toes > 30° external rotation	0 = no 1= yes
7. Foot position at initial contact, toes > 30° internal rotation	0 = no 1= yes
8. Stance width at initial contact < shoulder width	0 = no 1= yes
9. Stance width at initial contact > shoulder width	0 = no 1= yes
10. Initial foot contact symmetric	0 = yes 1= no
11. Knee flexion displacement before jumping >45°	0 = yes 1= no
12. Knee valgus displacement before jumping knee inside great toe	0 = no 1= yes
13. Trunk flexion at maximal knee angle, trunk flexed more than at initial contact	0 = yes 1= no
14. Hip flexion angle at initial contact, hips flexed	0 = yes 1= no
15. Hip flexion at maximal knee angle, hips flexed more than at initial contact	0 = yes 1= no
16. Joint displacement, sagittal plane	0=soft 1=average 2=stiff
17. Overall impression	0=excellent 1=average 2=poor

More in details, items from 1 to 6 indicate the jump-landing quality in terms of lower limbs and trunk positioning at the initial contact; from 7 to 11 the errors in positioning of the feet, from 12 to 14 allow assessing the lower extremity and trunk movements between initial contact and the moment of maximum knee flexion angle, the item 15 at the moment of maximum knee valgus; finally the last two items indicate an overall quality of the motion gesture. A maximal score of 19 can be achieved, representing the worst jump-landing performance.

It has been demonstrated as LESS score value equal or lower than 5 is associated with athletes who can be considered not at risk of ACL injury; conversely score greater than 5 indicate athletes at risk [179]. The evaluation has been performed for each of the three jumps; then, the median value has been considered to define athletes at risk injury and used as reference for the further analyses.

Sensor-based assessment phase: mCMJ and SLS

Considering both tasks, the data acquired during the static calibration in upright position were firstly used to perform the re-alignment of the sensor axes with the absolute reference system; then, the Mahony filter was applied to extract the orientation of the sensors by combining linear accelerations and angular velocities [43].

Two typologies of parameters were computed for assessing the leg stability and the load absorption capability.

Leg stability

Linear accelerations and angular velocities were used to estimate the orientation of the vertical axis ($\vec{s}$) of the sensor. The path covered by the projection of $\vec{s}$ on the horizontal plane placed at 1 cm below the inertial sensors was analyzed with parameters typically used in posturography. Following the equations proposed by Prieto *et al.* [45], we computed the following stability parameters:

- The total length of the path in the plane, named as PL:
- The total length of the path in antero-posterior direction, names as PL_{AP};
- The total length of the path in antero-posterior direction, names as PL_{ML};
- The area of the bivariate confidence ellipse that include at least 99% of the projection points, named as EA;

These parameters were computed for both tasks. For mCMJ, the parameters were then normalized for the stabilization time (Ts), that was defined as the time between the initial contact time with the ground, which was detected by the on status of the optoelectronic LED diodes, and the instant in which the leg can be considered stable, which was associated with the first minimum of the absolute value of the shank's angular velocity after the contact time, which guarantees to take into account the time period identified as the most likely for the injury occurrence [130]. Conversely, for SLS the parameters were normalized for the duration of the descending phase (T_{DP}) since it is associated with a greater stress for the knee joint with respect to the ascending one [144]. T_{DP} was defined as the time between the start and the end of the movement. Specifically, the start of movement was identified as the instant in which the standard deviation of the module of the three angles overcame five times the value of the average SD obtained during the static trial; the end of the movement was identified as the maximum value reached by the angle around the y axis, which approximately corresponds to the knee flexion axis, named as θ_{ymax}. The θ_{ymax} was considered as the index related to the leg mobility; specifically, lower was the value, lower the mobility [180,146].

The leg stability parameters allowed us to quantify the leg stability; in fact it has been shown as greater values of them correspond to greater instability after jump [142], which is considered as one of the main cause of ACL injury [130].

Load absorption capability

Load absorption capability were assessed only related to mCMJ. The root mean square (RMS) of the shank linear acceleration was computed both considering the vertical component (RMS_Z) and the module of the components along the xy horizontal plane (RMS_{xy}), both expressed in m/s^2. The parameters were normalized to Ts. Greater values of RMS indicate the poor capability of the athlete to absorb the load during the landing phase [145].

All the examined parameters, summarized in Table 13, were considered as features for the training and test of the machine learning algorithms in order to distinguish between two classes: athlete at risk or not, hereinafter class R and class NR. Regardless the type of parameter, all of them were averaged, finally across the five jumps or the five squats.

Table 13 – Feature selection for both motion tasks

Features		**mCMJ**	**SLS**
Leg stability	PL [cm]	✓	✓
	PLAP [cm]	✓	✓
	PLML [cm]	✓	✓
	EA [cm^2]	✓	✓
Load absorption	RMSz [m/s^2]	✓	
	RMSxy [m/s^2]	✓	
Leg mobility	θ_{ymax} [°]		✓
Time parameters	Ts [s]	✓	

T_{DP} [s]	✓

Machine learning algorithms

In this study, we decided to examine two different categories of supervised machine-learning algorithms, i.e. geometric and binary since they represent two of the most widespread algorithms for motion recognition [181]. Among geometric classifiers, we selected the support vector machine (SVM) and the k-nearest neighbor (kNN); instead the decision tree (DT) was chosen among binary algorithms.

SVMs are geometric supervised machine-learning algorithms that work on the identification of the hyperplane that guarantee the best separation of the features related to different classes. The kernel function, which is used to linearize the feature space, represents the fundamental parameter to be selected before the classification process. Specifically, we here tested three SVMs, considering the kernel function as linear (l-SVM), quadratic (q-SVM) and cubic (c-SVM).

kNN are geometric supervised machine-learning algorithms that perform the classification decision by identifying the most common class among the k-nearest neighbors and maximizing the distance among other classes. Thus, the equation for the computation of the distance represents the first parameter to be selected. Specifically, we here tested three kNN: the fine kNN (f-kNN), which considered the Euclidian distance to recognize different classes with the number of neighbors set to 1; the cosine kNN (c-kNN), which considered the cosine distance and the number of neighbors set to 10; and, the weighted kNN (w-kNN), which used the weighted Euclidian distance based on the squared inverse approach by selecting the number of neighbors equal to 10.

DTs are binary supervised machine-learning algorithms that predict the most likely class by creating a set of nodes, in which the classification process is performed through specific split criteria. In this study, the split criterion was based on the Gini index. In addition, the maximum number of split represents a fundamental parameter to be selected before the classification process. Specifically, we here tested three DTs: the coarse (c-DT), medium (m-DT) and complex DT (cx-DT), in which the maximum number of split was equal to 4, 20 and 100, respectively.

For further theoretical details on the selected classification algorithms, please refer to [12].

To summarize, we here compared nine machine-learning algorithms, as reported in Table 14.

Table 14 – List of tested machine learning-algorithms and acronyms

Geometric		**Binary**
SVM	**kNN**	**DT**
Linear (l-SVM)	Fine (f-kNN)	Coarse(c-DT)
Quadratic (q-SVM)	Cosine (c-kNN)	Medium (m-DT)
Cubic (c-SVM)	Weighted (w-kNN)	Complex (cx-DT)

By using the above-mentioned features, we evaluated the performance of all the selected machine-learning algorithm with the application of a 9-fold cross-validation. In this way, 30 subjects composed the dataset of training and the remaining nine the dataset of validation, in turn. The cross-validation is an approach that guarantees the robustness of the obtained performance [12]. Then, the algorithm performance was assessed by averaging across all the folds.

Performance evaluation

The classes, risk and not risk, estimated by means of the above-mentioned algorithms were compared by the reference value obtained through the LESS score. For each classifier, a 2x2 confusion matrix was then obtained. Successively, the algorithm performance were measured in terms of accuracy, F1-score and goodness index [12].

Accuracy (A) was computed as the ratio between the correct predicted risk classes and the total of predictions though the following equation:

$$A = \frac{TP + TN}{TP + TN + FP + FN}$$

where TP, TN, FP and FN represented true positive, true negative, false positive and false negative, respectively. Considering the positive as the class "no risk" (NR), a true positive and true negative were obtained when the algorithm correctly classifies the athlete at no risk (NR) and at risk (R) as it has been classified by the LESS score. Value close to 1 represents the perfect classifies and 0.80 is usually selected as threshold value for considering an optimum classifier [12].

The F1-score was computed as a harmonic average of the recall (Re) and the precision (P) value; where the recall represents the ratio between the true positive and the sum of the true and false positive; the precision (P) was, instead, computed as the ratio between the true positive and the sum of true positive and false positive. F1-score was calculated according to the following equation:

$$F1 - score = 2 \cdot \frac{(Re \cdot P)}{(Re + P)}$$

As for the A, F1-score can range from zero to one, with a value close to 1 indicating a perfect classifier and a threshold value of 0.80 allows identifying an optimum classifier.

Moreover, the goodness index (G) that represents the Euclidian distance in the receiver operating characteristic space between the tested classifier and the perfect one was computes as:

$$G = \sqrt{(1 - TP)^2 + (1 - TN)^2}$$

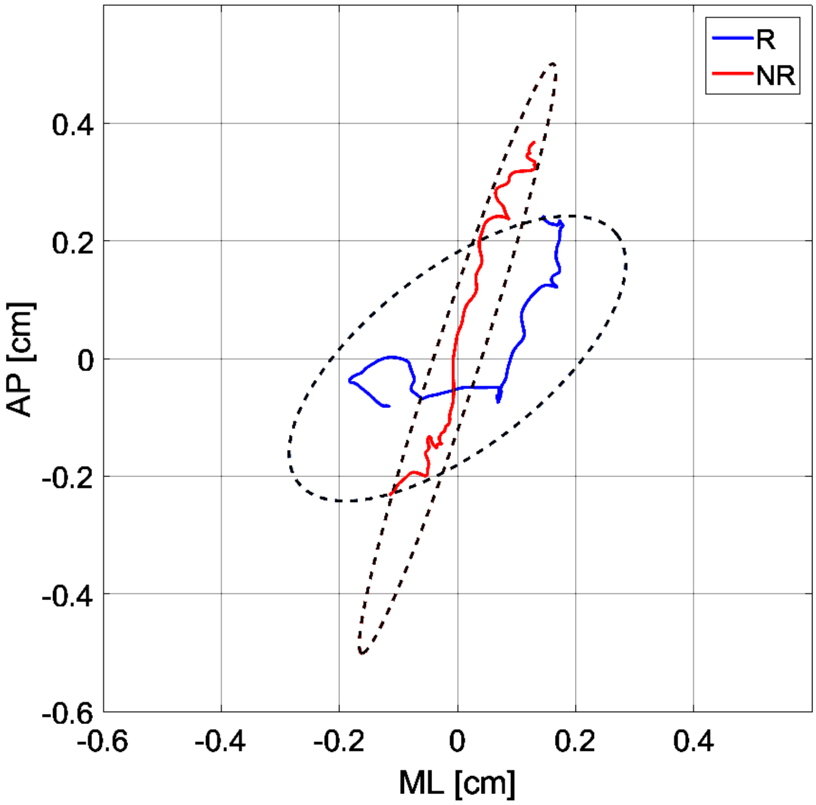
G assumes values from 0 to $\sqrt{2}$ and the following goodness range can be considered: (i) optimum when $G \leq 0.25$; (ii) good when $0.25 < G \leq 0.70$; (iii) random if $G = 0.70$; and (iv) bad if $G > 0.70$ [42].

After the validation of the algorithms, the feature importance was measured through the mean decrease accuracy (MDA) based on random forest [182,183]. MDA represents the average loss of accuracy achieved by the random forest on data out-of-bag (OOB), where the OOB approach consisted in three steps. Firstly, one feature in turn was excluded from the model and the prediction error was computed; secondly, the predictor variables of the new model were permuted to loss the correlation with the true class and the prediction error was computed on this new dataset; finally, the difference between the two predictor errors was computed and averaged across all the turns to obtain MDA, expressed in percentage. Greater is the value of MDA, greater is the feature importance.

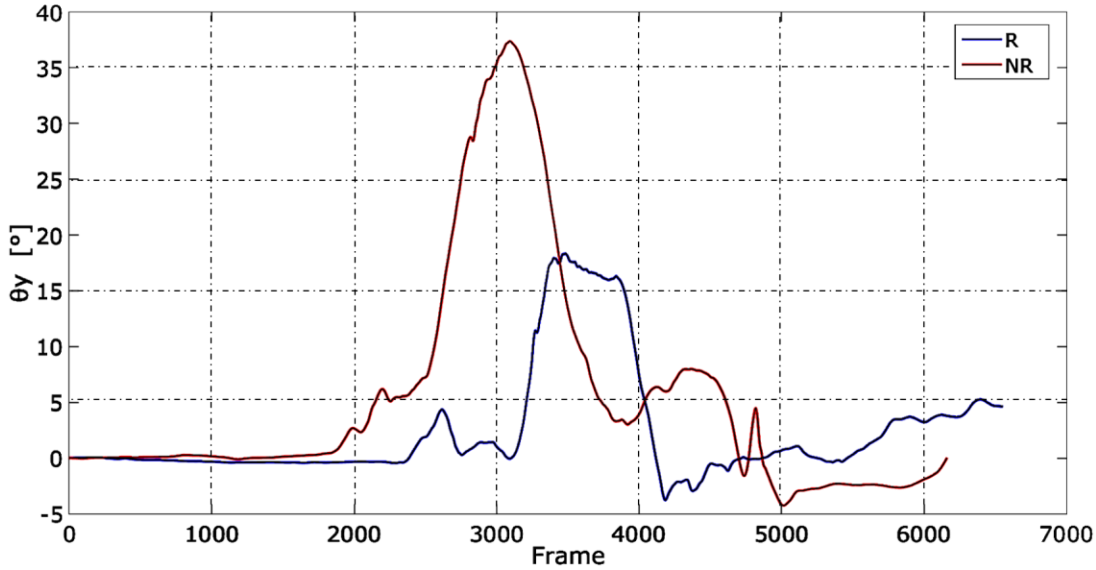
Finally, the correlation between the most important features and the LESS score was computed by means of Spearman's correlation tests, considering a significance level set to 0.05. The absolute value of r can be interpreted as: (i) no correlation, if $|r| \leq 0.1$; (ii) mild/modest correlation, if $0.1 < |r| \leq 0.3$; (iii) moderate correlation, if $0.3 < |r| \leq 0.6$; (iv) strong correlation, if $0.6 < |r| < 1$; and, finally, (v) perfect correlation, if $|r| = 1$, as in [38,184].

Results & Discussions

The results of the LESS analysis led to the identification of 26 athletes belonging to the class NR and the remaining 13 to the class R. In particular, the mean value of the LESS was equal to 3.5 and 7.5 for NR and R group, respectively. As an example, the path length of the vertical axis projection on the horizontal plane obtained during a jump task, as well the waveform of the angle θ during a squat task performed by one subject belong to the R and NR group were reported in Figure 20.



(a)



(b)

Figure 20. Example of (a) path length in xy plane during mCMJ and (b) angle waveform during SLS. Blue and red lines indicate results related to a subject in R and NR group, respectively.

By analyzing the graphs, it is possible to observe how the subject belong to the R group was characterized by a greater excursion of the path length in ML direction, leading also to a greater value of the ellipse confidence area when landing after a monopodalic countermovement jump, as well by a lower value of the knee angle during a single leg squat movement. More in general, the mean values and standard deviations of the computed features for each group are reported in Table 15.

Table 15 – Mean (SD) of the computed features for the R and NR group.

Task	Features	R	NR
mCMJ	TS [s]	0.21 (0.04)	0.33 (0.06)
	PL [cm]	2.7 (0.9)	2.9 (0.8)
	PL_{AP} [cm]	2.8 (0.2)	1.1 (0.1)
	PL_{ML} [cm]	1.5 (0.5)	1.6 (0.3)
	EA [cm^2]	1.5 (0.2)	0.7 (0.2)
	RMS_z [m/s^2]	247.4 (85.6)	95.6 (19.4)
	RMS_{xy} [m/s^2]	169.4 (26.7)	70.1 (14.9)
SLS	T_{DP} [s]	3.22 (0.95)	3.90 (1.23)
	PL [cm]	0.8 (0.1)	0.8 (0.3)
	PL_{AP} [cm]	0.6 (0.1)	0.6 (0.2)
	PL_{ML} [cm]	0.4 (0.1)	0.5 (0.2)
	EA [cm^2]	0.5 (0.0)	0.7 (0.0)
	θ_{ymax} [°]	16.8 (2.7)	26.0 (5.3)

By analyzing these results, it can be observed as athletes in R group generally showed a greater path length in AP direction and a greater value of the EA with respect NR, as well a reduction of stabilization time related to the leg stability evaluation when performing mCMJ. Similarly, the load absorption parameters were found higher when computed on data gathered from athletes at risk of injury. Focusing on SLS, stability parameters showed similar behavior on both groups; conversely R group was characterized by a lower leg mobility and a lower descending phase time.

Figure 21 shows the confusion matrices calculated for all the examined classifiers.

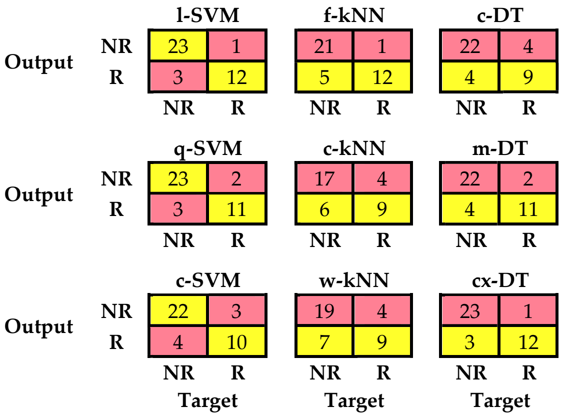


Figure 21. Confusion matrices for all the tested classifiers. NR and R stands for not-risk and risk class.

Table 16 shows the results in terms of accuracy, F1-score and goodness index achieved by all the tested classifiers and derived from the confusion matrices.

Table 16 – Accuracy (A), F1-score and goodness index (G) achieved by the nine tested classifiers.

	A	F1-score	G
l-SVM	0.95	0.96	0.08
q-SVM	0.87	0.87	0.19
c-SVM	0.82	0.81	0.28
f-kNN	0.85	0.86	0.21
c-kNN	0.67	0.71	0.46
w-kNN	0.74	0.75	0.35
c-DT	0.79	0.79	0.34
m-DT	0.85	0.85	0.22
cx-DT	0.90	0.90	0.14

By focusing on the accuracy, the linear SVM achieved the best results, equal to 0.96; instead, the worst was associated with the cosine kNN with a value of 0.67. More in general, six out nine of the tested classifiers overcame the optimum threshold set to 0.80. Similar outcomes were obtained by considering the F1-score, whose values ranged from 0.71, which was associated with the cosine kNN, to 0.96, which was related to the linear SVM. As regards the F1-score, the same six out nine classifiers achieved the performance of optimum classifier. By considering the G index, the best performance was achieved by the l-SVM, *i.e.* a value equal to 0.08 and the worst by the c-kNN, *i.e.* a value equal to 0.46. As concern G, only five classifiers fell into the optimum range with the cubic SVM that passed only the threshold related to the accuracy and F1-score.

The selection of the right model parameters, such as kernel function for SVM, distance equation for kNN and number of split for DT, appears to be a fundamental step for the classification process since it can lead to a worsening of the algorithm performance. This result is in line with previous studies, in which it has been demonstrated as the tuning of model parameters should be always conducted to avoid misclassifications [185,186]. After the right selection of the model parameters, by combining the results we can assess that l-SVM, q-SVM, f-kNN, m-DT and cx-DT meet all the criteria to be considered as optimum classifier. Specifically, the above-mentioned classifiers achieved encouraging results up to more than 20% with respect previous published applications of artificial intelligence in this context [177,178]. Among the five optimum classifiers, the linear support vector machine reveals itself as the best performing considering all the synthetic indices. In addition, we can assess that the l-SVM should be chosen not only for the highest value of A and F1-score, as well the lowest of G, but also taking into account that: (i) it is characterized by a higher value of prediction speed, a lower memory usage and an easier interpretability of the results with respect q-SVM due to the lower order of the kernel function [188]; (ii) SVM outperforms kNN in managing outliers data, reducing the number of false positive and false negative rate [189]; and, (iii) geometric classifiers are generally more robust across subjects with respect decision trees, which apply a threshold-based classification logic [190].

By summarizing, we can speculate that the linear SVM, more than others, may be introduce as a screening tool since for the identification of the athletes at higher risk injury if it is fed with data gathered from athletes when performing jump and squat tasks. In addition, the use of the artificial intelligence based on quantitative and objective measures could permit to overcome the intrinsic limitation of subjective evaluation, as the landing error scoring system is.

The MDA values for all the used features in order to understand their importance are reported in Figure 22.

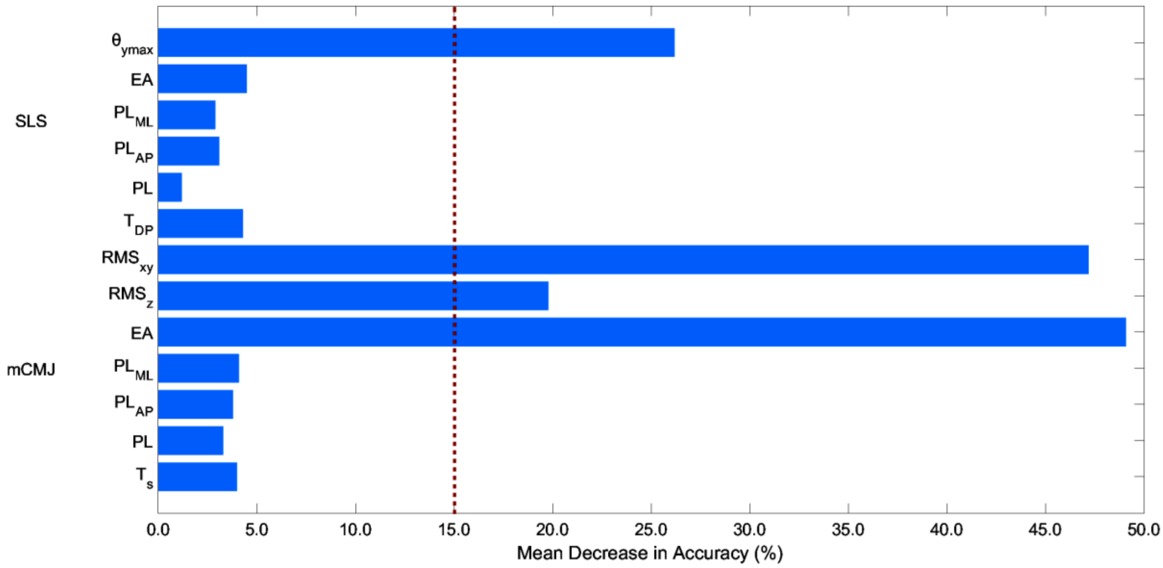


Figure 22. Mean Decrease in Accuracy (%) for all the used features. Dotted red line indicate the importance threshold of 15.0 %.

By analyzing the histograms, the ellipse area computed during the monopodalic countermovement test was associated with the highest value of the MDA, i.e. 49.2%, leading to define it as the most important feature of the dataset. A high importance was also found for the RMS_{xy} computed during the mCMJ; an MDA greater than 15% was also achieved by the RMS_z gathered during the mCMJ and the θ_{ymax} computing for the single leg squat. MDA values lower than 5.0% were obtained by all the other features. These results allow us affirming that only the four mentioned features present significant differences that permit to distinguish the athletes at higher risk ACL injury. Consequently, the involvement of the remaining nine parameters among the feature set can be avoided, permitting to reduce the computational time of the automatic classification algorithm.

The sensitivity of the parameters related to the load absorption capability and the leg mobility in the recognition of athletes at higher risk is, instead, in line with the outcomes already reported in literature. As concerns the load absorption, Shimokochi *et al.* [191] demonstrated as prevention programs addressed to increase the athlete ability in reacting to the load during the landing phase after jump can help to reduce the risk of injury. In addition, this aspect is emphasized in female athletes, who adopt an absorption strategy that consists in the use of distal joints, causing an increase of the risk of ACL injury with respect to male players [192]. As for the leg mobility, knee angle joint has been shown as one of the main aspects to be investigated during motion tasks for the assessment of ACL injury risk in different sports, such as basketball, soccer and volleyball [165,193]. Among the stability indices, only the confidence ellipse area reveals itself as useful predictor in this context; this finding is in contrast with the ones reported in the study conducted by [194], in which the absence of correlation between knee stability parameters and ACL injury was assessed in soccer and handball players. However, it is worth underlying that the outcomes in [194] were obtained through semi-static tests, i.e. the execution of the star excursion balance, rather than jump-based tasks, and with a different population; indeed it is recognized as the evaluation of the instability during landing phase after a jump can be used as predictor factor [130]. By combining the results on the best performing classifier and the most important feature, we can assess that the evaluation of leg stability, leg mobility and load absorption capability in athletes performing monopodalic jump and single leg squat tasks and the successive application of a machine-learning algorithm based on linear support vector machine can be a useful screening tool for the identification of athletes at higher ACL injury risk. In addition, it is also possible to suggest to perform only the monopodalic countermovement jump, since the exclusion of the θ_{ymax}, which is the only important parameters related to the squat task, did not lead to a significative change in the algorithm performance. One of the main advantage of the proposed algorithm can be ascribed to the possibility to apply such procedure without the necessity of a skilled operator that results, instead, fundamental for the computation of the LESS score in order to avoid the limitation related to the subjectivity of the operator [169].

Considering the correlation analysis, the four features that reached a MDA at least equal to 15.0% showed different behavior, as reported in Table 17.

Table 17 – Accuracy (A), F1-score and goodness index (G) achieved by the nine tested classifiers.

	r	***p*-value**
EA	0.88	0.01
RMS_z	0.25	0.12
RMS_{xy}	0.59	0.04
θ_{ymax}	0.60	0.03

Considering the goodness of the correlation, EA was found the only one that strongly correlated with the LESS, whereas RMS_{xy} and θ_{ymax} reached a moderate correlation and RMS_z a modest correlation. Thus, the analysis of the ellipse area index permits an objective evaluation of the knee stability, revealing itself as a predictive factor, and a better quantification of changes over time also when functional scales appear no longer sensitive. In particular, since EA index is not a discrete variable as the functional scales used in clinics, it could permit to have a greater resolution in the discrimination of different risk levels, as well, not presenting a maximum possible value, it could guarantee to overcome the well-known intrinsic limit of clinical score associated with the saturation effect at the upper limit of the scale [195].

An instrumented protocol based on wearable sensors to reliably quantify knee stability: application in football

Introduction

With an increasing worldwide incidence, Anterior Cruciate Ligament (ACL) ruptures represent the most recurrent and critical injuries related to the knee joint [196,197], accounting for 20% of total knee injuries [198] and most 50% of knee ligament tears [199]. ACL rupture is mostly common during sports requiring cutting and pivoting movements, in conditions of spatial and temporal uncertainty, like soccer. In adult male soccer players, in fact, the ACL injury yearly rate ranges between 10 and 35 cases per 1000 hours of practice [200].

Following ACL rupture, a surgical intervention is very often required. After surgery, the athlete is involved in a long rehabilitation process, aiming at returning to unrestricted sports practice in the safest possible way. However, when dealing with outcomes of the rehabilitation process, a lack of consensus exists about the criteria/thresholds that must be used to determine the physical readiness to return to the preinjury activity level [201,202]. Indeed, when a quantitative assessment is performed, different (and often conflicting) evaluation- and timed-based protocols exist [203].

Traditionally, both laboratory- and functional/field-based tests are carried out. Among the former, current protocols commonly consider muscle force symmetry during isometric or isokinetic contractions, which can provide accurate and repeatable values [202,204]. However, the performed movement is often influenced by the constraints imposed by the instruments used - such as the isometric leg press or the isokinetic machine for knee flexion-extension - and it rarely reproduces sport-specific tasks and typical isotonic contractions. Conversely, functional and field-based tests allow for the reproduction of more complex and realistic movements, including dynamic muscle contractions associated with sport-specific tasks. Functional hop tests and agility tests based on change-of-direction movements are common examples [205-207]. Nevertheless, these tests are generally oriented to analyse the overall outcome rather than how the considered movement is executed, thus failing to provide information related to the quality and safety of the movement itself [208]. Even though the outcomes of current RTS test protocols suggest clearance for return to unrestricted activity, the probability of a new traumatic episode is still very high. Specifically, it has been found that new injury rate is about 29.5 % within two years after RTS, with 20.5 % and 9.0% referring to contralateral and ipsilateral injury, respectively [209]. This highlights the need to implement new protocols and informative indices for the assessment of athletes with ACL reconstruction (ACLR) that focus on realistic and sport-related movements and provide quantitative and reliable information on movement quality.

In this perspective, wearable magneto-inertial measurement units (MIMUs) may represent a good compromise between laboratory- and field-based tests. MIMUs, which typically include embedded 3D accelerometers and gyroscopes, may provide quantitative information during sport-specific, multi-joint and high intensity-based tasks. The application of MIMUs is extensive both in clinical movement analysis [210-213] and in sport performance context [214,215]. More recently, these sensors have also been applied for the investigation of risk factors associated to ACL injury [142,216-218]. In a recent prospective case-control study, Dan and colleagues explored the utility of an MIMU placed on the tibia together with a pressure sensing mat system. In their work, the aim consisted to detect differences in motions in three cohorts including patients with ACLR, non-athletic controls and elite athletes. Through data obtained from both systems, the authors found between-limb malalignments in the ACLR group, which was speculated to be associated with a greater risk of re-injury [216]. In a recent case-report study, Molinaro and colleagues compared lower-limb stability of a basketball player before and after ACLR using a tibia-mounted inertial sensor. Significant between-limb differences were found before the injury as well as between pre and post ACL intervention within the same limb (Molinaro *et al.*, 2020).

Some studies combined MIMUs with stereophotogrammetric systems or force platforms to validate the proposed MIMU-based application with respect to gold standard methods [219-223]. Dowling and co-workers found that feedback based on kinematic measurements from an inertial sensor-based system can be used to modify key ACL injury risk metrics, like knee flexion angle, trunk lean and knee abduction moment during jump landing [220]. Pratt and Sigward reported that the ratio between thigh angular velocities of surgical and non-surgical limb was strong enough to identify knee power deficits with high sensitivity and specificity during monopodalic tasks [221,222]. It is thus clear that MIMU-based technologies can be effectively used to obtain objective information about risk factors somehow associated to ACL injury.

However, the existing literature mainly focused on single-task protocols, generally based either on drop/countermovement jumps or on loading tasks. Despite the validity of hop tests to monitor rehabilitation and quantify recovery after ACLR has been reported [208,224,225], very few studies are focused on the instrumentation of hop tests with wearable technologies. In addition, although fundamental to set basis for the implementation of a suitable and accurate sensor-based protocol, the reliability of parameters obtained from MIMU data is rarely taken into consideration [202].

The purpose of the present study is to propose a wearable sensor-based protocol and test the reliability of a set of parameters gathered from MIMU data, which are related to knee instability. To this aim, Crossover Hop Test and Single Leg Squat movements were performed by young healthy soccer players wearing two MIMUs on the tibia and foot segments. Our hypothesis is that, if reliable, parameters obtained from the proposed protocol may allow to objectively quantify the dynamic knee stability in athletes, playing a role in investigating the multifactorial phenomenon of ACL injury.

Materials & Methods

Participants

Seventeen non-professional young male soccer players (age: 21.5 ± 3.2 years (mean ± SD); stature: 1.84 ± 0.05 m; body mass: 74 ± 7 kg) participated in the present observational study. Inclusion criteria were: (*i*) no history of significant lower limb injuries involving surgery or causing ongoing disability, (*ii*) 18 to 40 years of age, and (*iii*) Tegner Activity Score ≥ 6 [226]. The dominant lower limb was identified for each participant as the limb that was used to kick a ball twice [227]. All participants were right limb dominant, except one. Before starting data acquisition, an informative paper was provided, and written consent was obtained from each participant. The study was approved by the University of Rome “Foro Italico” committee for research (CAR 19/2020). All the procedures were conducted in accordance with the Declaration of Helsinki.

Experimental Setup

Two magneto-inertial measurements units (MIMUs) (Gyko, Microgate S.r.l., Italy) were attached on the foot dorsum and on the medial upper portion of the tibial crest of each participant using *ad hoc* straps (Figure 23), to limit their oscillations relative to the underlying segment [228].

Figure 23. MIMU placement: ad hoc straps and tape were used to fix MIMUs on the foot and tibia.

MIMUs were positioned by the same operator and paying attention to align one of the MIMU axes (the x-axes) with the longitudinal axis of the relevant segment. Each MIMU includes 3D gyroscopes, linear accelerometers and magnetic sensors (± 2000°/s, ± 16 g, and ± 4800 μT of full-range scale, respectively), measuring 3D angular velocity, linear acceleration and magnetic field vector at a sampling frequency of 500 Hz. Considering the full-range scale and the sampling frequency, these MIMUs proved to be particularly suitable for the assessment of high-intensity sports movements [30,143]. Data acquired by the MIMUs were transmitted via Bluetooth to a laptop. The two MIMU data streams were electronically synchronized.

Experimental Protocol

Tests were carried out in the Laboratory of Bioengineering and Neuromechanics of Movement of the University of Rome "Foro Italico". Before starting data acquisitions, a standardised 5-minute warm up on cycle-ergometer was completed by each participant. Participants were first asked to perform two preliminary tests aimed at assessing the presence of asymmetries in terms of knee joint range of motion (RoM) and force exertion. For the former, the flexion-extension RoM of the knee joint was measured using a goniometer following the indications provided by [229]. Specifically, maximal knee joint extension was measured by asking the participants to lie in a supine position with their heel placed on a pillow, thus allowing for knee hyperextension, whereas maximal knee flexion was measured by asking participants to flex their knee in order to place the heel as close as possible to their gluteus. For the force exertion, three countermovement jumps (CMJs) were performed by each participant on two force platforms (0.6 x 0.6 m each, AMTI, USA, sampling frequency: 1000 Hz). Participants started from an upright position, with each foot on a force platform and with their hands fixed on the hips [230]. They were asked to perform a maximal CMJ three times, with a pause of at least 20 s between two consecutive jumps. Parameters related to the vertical component of ground reaction force were then extracted for both limbs as detailed in the Data processing section.

After the preliminary tests, two functional tests were performed by each participant: The Single Leg Squat Test (SLS) and the Crossover Hop Test (CHT). These two tests were selected because they include single-leg closed-chain movements typical of open skill sports. In addition, they are commonly proposed in the literature to assess readiness to Return to Sport after ACL injury and reconstruction [231,232]. A brief description of each test is reported below:

- *Single Leg Squat Test (SLS)* [231]. Starting from a standing bipodal position, participants were required to switch to a single leg support with the other leg lifted off the ground in front of the body. Participants were then asked to perform a squat. The arms were extended forward, and participants had to squat as much as they can maintaining balance and to get up to the initial bipodal position with knee fully extended.

- *Crossover Hop Test (CHT)* [232]. Participants were asked to hop forwards three times on a single leg while alternately crossing over a straight line marked on the floor, trying to cover the greatest distance possible. They were not asked to necessarily stop and keep their position at the end of the trial, i.e. at the third hop landing. They started from a bipodal standing position, switch to a single leg support and were then asked to keep their hands on the hips throughout the entire test and to hop as far as possible. The total hopped distance, from the start line to the heel of the landing leg, was recorded.

Each test was performed three times for each side (the one instrumented with the MIMUs), resulting in six trials for each participant (three with the dominant and three with the non-dominant limb). The order of the tests and side was randomized for each participant to control for any order effects associated with repeated testing.

Data Analysis

Data acquired by each MIMU were analyzed using *ad hoc* developed Matlab® (The MathWorks Inc., Natick, MA, USA) scripts and functions.

Preliminary test – CMJ

For each CMJ, the vertical component of the GRF measured by force plates (GRFv) was considered for both legs. The time interval between the end of the unweighted phase and the start of the flight time was then identified for each trial and considered for further analysis. The end of the unweighted phase was automatically identified as the instant in which the first inflection point of the curve occurred, whereas the start of the flight time was identified as the instant in which the vertical component was equal to zero. To obtain the net vertical force exchanged by each participant with the floor, participants' weight was subtracted from the segmented data.

SLS

For the SLS test, the angular displacement around the Y axis of the MIMU placed on the tibia (corresponding to the leg medio-lateral axis and approximately to the knee flexion axis) was obtained by means of a complementary filter applied on the acceleration and angular velocity data [43]. Task segmentation entailed the identification of three instants of time: the beginning of the squat movement (SLS_{start}), the end of the eccentric phase (EPe), and the end of the whole task (SLS_{end}). To identify these instants, a moving standard deviation of 10-sample window (σ) was calculated on the above-mentioned angular displacement and multiplied by a factor of 10. SLS_{start} was then defined as the instant in which the following criterion was met: $\sigma > 2 \cdot \sigma_{static}$, where σ_{static} is the standard deviation of the angular displacement calculated in the first 1000 samples when the participant was still, before the trial. EPe corresponded to the instant in which the maximum of the angular displacement curve occurred (Figure 24), whereas SLS_{end} was defined as the time instant when the angular displacement curve returned to its initial value, the same as in SLS_{start}, i.e., the participant was back to his initial position (Figure 24).

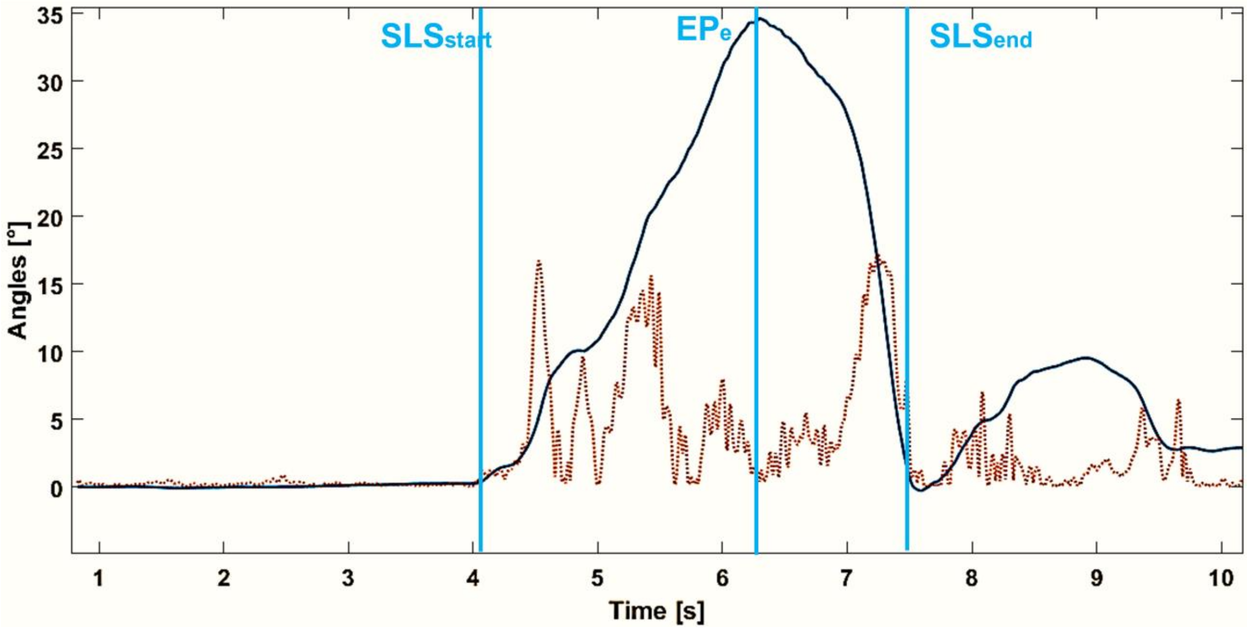


Figure 24. Angular displacement around the Y axis of the tibia MIMU (solid line) and its moving standard deviation of 10-sample window (dotted line). The three instants of time identified for SLS phase segmentation (SLS_{start}, EP_e, SLS_{end}) are also depicted as vertical red lines.

CHT

For the CHT, the acceleration measured by the MIMU located on the foot was expressed with respect to a vertically aligned inertial reference frame [43]. The task was then segmented according to Ahmadian *et al.* [228] by identifying the take-off (TO) and landing (LA) time instants of each hop as follows: TO corresponded to the instant where the derivative of the angular velocity module of the foot sensor falls below a value of -0.6 rad/s^2, whereas LA was identified as the first peak occurring in the first derivative of the acceleration norm having an amplitude greater than 7 m/s^3 (Figure 25).

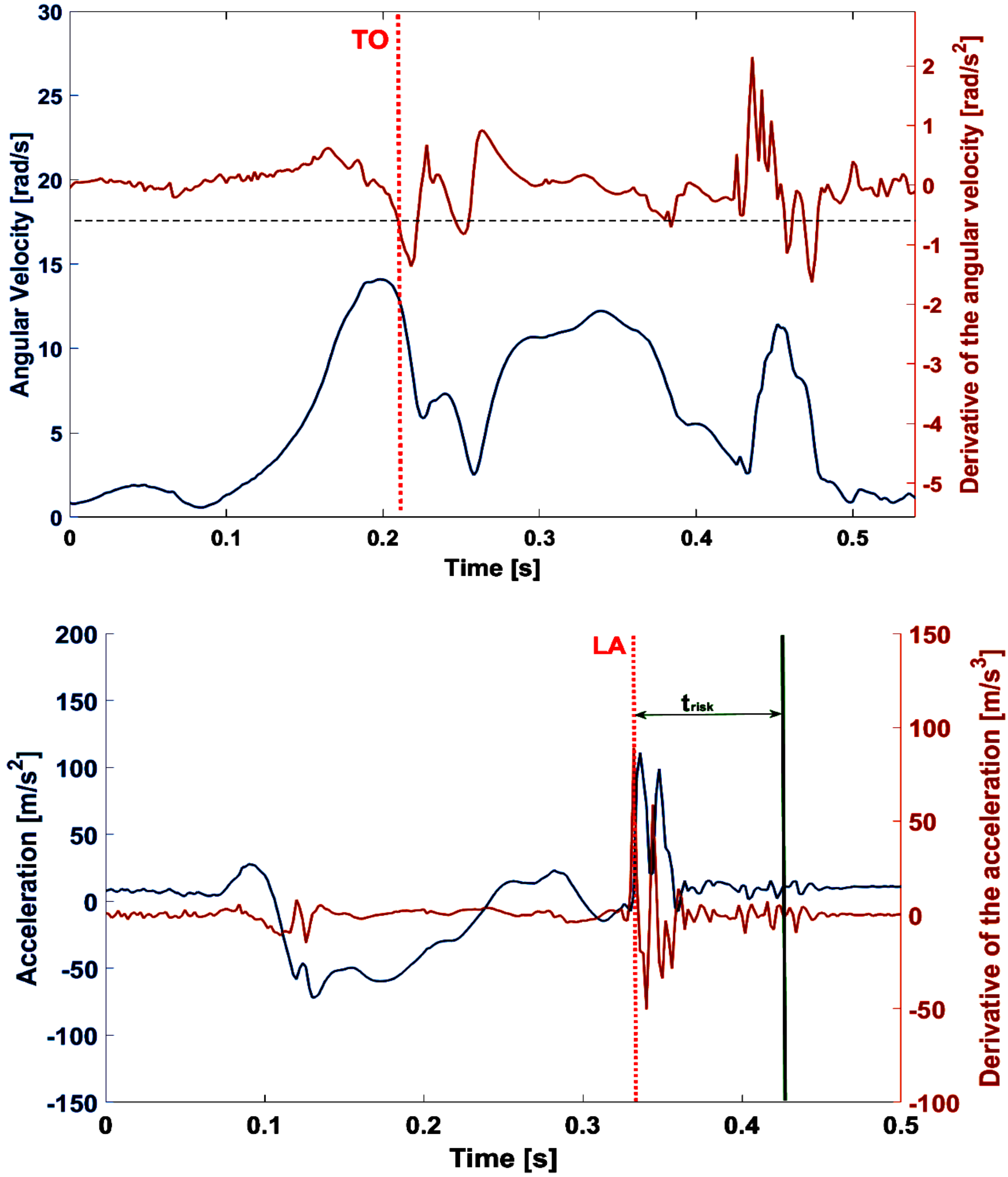


Figure 25. CHT phase segmentation: a) Top panel: foot-based MIMU angular velocity magnitude (dark blue) and its derivative (red) used to identify the take-off instant (TO, indicated with a red dashed line); b) Bottom panel: foot-based MIMU vertical acceleration (dark blue) and derivative of the acceleration magnitude (red) used to identify the landing instant (LA, indicated with a red dashed line). The 100 ms time window considered for the estimation of parameters related to the knee joint stability is also indicated (trisk indicated as a black vertical line).

According to the existing literature, ACL injuries mostly occur in the first 100 ms after the contact of the foot (or Initial Contact, IC) with the ground [130,233,234]. Therefore, a time window of 100 ms (t_{risk}) after LA was considered for the estimation of parameters related to the knee joint stability (see Table 18).

Table 18 - List of the MIMU-based parameters estimated for the Single Leg Squat test (SLS) and the Crossover Hop Test (CHT).

TYPE	PARAMETER	ACRONYM	MEAS. UNIT	DEFINITION	SLS	CHT
Temporal parameters	Total Test Duration	T_{tot}	s	Time interval between the beginning and the end of the motor task. For the SLS, only the eccentric phase was considered.	✓	✓
	Flight Time	FT	s	$LA_i - TO_{i-1}$		✓
	Contact Time	CT	s	$TO_i - LA_{i-1}$		✓
Acceleration based stability parameters	Root Mean Square of the foot acceleration	$RMSa_{foot}$	m/s^2	$RMSa_{foot} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} a_{i\,foot}^2}$	✓	✓
	Root Mean Square of the leg acceleration	$RMSa_{leg}$	m/s^2	$RMSa_{leg} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} a_{i\,leg}^2}$	✓	✓
Angular velocity based stability parameters	Root Mean Square of the foot angular velocity	$RMS\omega_{foot}$	°/s	$RMS\omega_{foot} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} \omega_i^2}$	✓	✓
	Root Mean Square of the leg angular velocity	$RMS\omega_{leg}$	°/s	$RMS\omega_{leg} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} \omega_i^2}$	✓	
	Peak of foot angular velocity	$\omega peak_{foot}$	°/s	Peak of the angular velocity signal measured by the foot-mounted MIMU during T_{risk}	✓	✓
	Peak of the leg angular velocity	$\omega peak_{leg}$	°/s	Peak of the angular velocity signal measured by the leg-mounted MIMU during T_{risk}	✓	✓
Parameters related to the tibia acceleration pattern on the YZ plane. [45,235,236]	Sway path of the leg acceleration	SP	m/s^2	Total length of the acceleration on the plane described by the y-z acceleration components	✓	
	Sway Area	SA	m^4/s^4	Area of the 90% prediction ellipse which encloses approximately 90% of the points on the acceleration path	✓	
	Eccentricity of the 90% prediction ellipse used for the Sway Area calculation	SAecc	dimless	$SAecc = \sqrt{1 - \frac{b^2}{a^2}}$ where a is the semi-major axis and b is the semi-minor axis of the 90% prediction ellipse used to calculate SA	✓	

Parameter Extraction

For the CMJs, two parameters were computed from the GRFv within the segmented time window: the maximum of the GRFv (F_{max}) expressed in N, and the relative net impulse (AUC_F), i.e. the net impulse normalised with respect the athletes' body mass and thus expressed in m/s according to Kirby [237].

For the SLS and CHT tests, a set of parameters related to temporal aspects of the motor task, as well as knee stability was estimated. The choice of these parameters was based on the existing literature dealing with MIMU-based stability assessment both at knee and different body levels. Specifically, on the one side acceleration based measures collected at different body levels and on the tibia have been associated to stability and knee loads [235,238,239]. On the other side, angular velocity signals have been considered when investigating ACL injury risk and their correlation with the external knee abduction moment, proven to be a strong indicator of ACL injury risk, was reported [219,221,240]. The complete and detailed list of the estimated parameters is reported in Table 18.

To investigate the presence of possible asymmetries between the dominant and non-dominant side, the Limb Symmetry Index (LSI) was then calculated for all extracted parameters as follows:

$$LSI = \frac{non\ dominant\ limb}{dominant\ limb} \cdot 100 \qquad (1)$$

LSI is commonly used to investigate asymmetries between the injured and non-injured limbs in the assessment of RTS readiness after ACL injury [204]. According to the existing literature, LSI values ranging from 85% to 115% are considered as indicators of physiological between-limb symmetry [241].

Statistical Analysis

To test intra-participant reliability, the Intraclass Correlation Coefficient (ICC) was calculated for each parameter and each test, over the three trials, based on absolute-agreement and 2-way mixed-effects model (Koo & Li, 2016). ICC values were considered as "poor" (ICC < 0.39), "fair" (0.40 < ICC < 0.59), "good" (0.60 < ICC < 0.74) and "excellent" (ICC > 0.75) [38,242]. This analysis allowed to understand if the intra-subject variability in performing the same task in successive repetitions is negligible or not.

For each task and each parameter, the median value over the three performed trials was than extracted and averaged across the participants. Standard deviations were also computed. For the CHT, only the second hop was considered for each trial, due to the high variability characterising the take-off and landing technique related to the first and the third hops, respectively [243]. Statistical analysis was performed using the IBM SPSS Statistics software (v23, IBM Corp., USA), with the alpha level of significance set to 0.05.

Results

Preliminary Test

Knee joint RoM evaluation excluded functional limitations during knee joint flexion-extension. Maximal extension values were 2 ± 1° both dominant and non-dominant limb, whereas maximal knee flexion was found to be 137 ± 1° and 138 ± 2° for dominant and non-dominant limb, respectively. Results obtained during the CMJ tasks are reported in Table 19. Overall, a physiological symmetry between the dominant and non-dominant limb was found during a multi-articular closed-chain movement as the CMJ, both in terms of F_{max} and AUC_F.

Table 19 - Results of the two parameters estimated during the CMJ (mean ± standard deviation). The LSI and ICC values are also reported: * p<0.05, ** p<0.01. DOM: dominant limb, NON-DOM: non dominant limb.

CMJ	**DOM**	**NON-DOM**	**LSI** [%]	**ICC**	
				DOM	**NON-DOM**
F_{max} [N]	520.6 ± 73.6	482.0 ± 67.9	93 ± 10	0.88*	0.87*
AUC_F [m/s]	2.2 ± 0.2	2.1 ± 0.2	97 ± 8	0.93**	0.92**

SLS and CHT

Tables 20 and 21 report the results obtained from the analysis of the two functional tests (SLS and CHT), together with the ICC values for all parameters. Most parameters displayed good to excellent reliability [38,242], both in SLS and CHT. The values of the LSI for each estimated parameter are also reported. As expected, a physiological symmetry [241] was displayed by the participants over all parameters and in both tests. For the CHT, the mean ± standard deviation values in terms of distance covered were 4.94 ± 0.58 m for the dominant and 4.91 ± 0.47 m for the non-dominant limb, resulting in LSI of 99 ± 8%. ICC values were 0.71 and 0.83, for the non-dominant and dominant limb, respectively (p<0.01).

Table 20 - Results of the parameters estimated during the SLS (mean ± standard deviation). The LSI and ICC values are also reported: * p<0.05, ** p<0.01. DOM: dominant limb, NON-DOM: non dominant limb.

SLS	**DOM**	**NON-DOM**	**LSI** [%]	**ICC**	
				DOM	**NON-DOM**
T_{tot} [s]	2.2 ± 1.1	2.3 ± 0.8	109 ± 36	0.66*	0.67**
$RMSa_{foot}$ [m/s^2]	0.4 ± 0.4	0.2 ± 0.1	95 ± 45	0.74*	0.29*
$RMSa_{leg}$ [m/s^2]	0.6 ± 0.2	0.6 ± 0.3	102 ± 25	0.64*	0.67*
$RMS\omega_{foot}$ [°/s]	11.4 ± 5.7	17.2 ± 5.6	112 ± 55	0.63*	0.64*
$RMS\omega_{leg}$ [°/s]	28.6 ± 5.6	28.7 ± 5.7	103 ± 18	0.66**	0.76*
$\omega peak_{foot}$ [°/s]	63.0 ± 40.1	51.6 ± 22.9	103 ± 53	0.68*	0.50*
$\omega peak_{leg}$ [°/s]	74.5 ± 22.8	74.4 ± 28.7	103 ± 38	0.60*	0.42
SP [m/s^2]	192.3 ± 70.3	213.5 ± 87.3	113 ± 37	0.60**	0.60*
SA [m^2/s^4]	36.4 ± 22.7	37.7 ± 20.5	107 ± 36	0.76*	0.65*
SAecc [dimless]	0.8 ± 0.1	0.8 ± 0.1	97 ± 9	0.70**	0.70*

Table 21 - Results of the parameters estimated during the CHT (mean ± standard deviation). The LSI and ICC values are also reported: * p<0.05, ** p<0.01. DOM: dominant limb, NON-DOM: non dominant limb.

CHT	**DOM**	**NON-DOM**	**LSI** [%]	**ICC**	
				DOM	**NON-DOM**
T_{tot} [s]	1.6 ± 0.2	1.7 ± 0.2	103 ± 7	0.82**	0.84*
CT [s]	0.4 ± 0.1	0.4 ± 0.1	102 ± 15	0.74**	0.77*
FT [s]	0.3 ± 0.0	0.3 ± 0.0	103 ± 8	0.46	0.43*
$RMSa_{foot}$ [m/s^2]	82.9 ± 9.9	76.4 ± 12.9	93 ± 13	0.45	0.42
$RMSa_{leg}$ [m/s^2]	67.8 ± 14.6	62.7 ± 21.9	88 ± 26	0.72*	0.25
$RMS\omega_{foot}$ [°/s]	509.9 ± 108.8	504.2 ± 108.9	96 ± 16	0.63*	0.66*
$RMS\omega_{leg}$ [°/s]	429.7 ± 97.4	401.1 ± 97.6	91 ± 18	0.63*	0.50*
$\omega peak_{foot}$ [°/s]	1294.9 ± 441.1	1168.8 ± 366.7	91 ± 23	0.70*	0.65*

$\omega peak_{leg}$ [°/s]	830.8 ± 280.7	704.7 ± 275.0	84 ± 25	0.60**	0.66*

Discussions

The present study proposes an instrumented protocol based on the use of wearable sensors to reliably quantify knee stability-related parameters during the execution of two tests commonly used for RTS assessment after ACLR, i.e. the Single Leg Squat (SLS) and the Crossover Hop Test (CHT).

A set of temporal and both acceleration and angular velocity based parameters descriptive of the knee movement during specific phases of the abovementioned motor tasks was selected based on previous literature [221,222,239].

Two preliminary tests were performed to assess the presence of asymmetries in terms of knee joint range of motion (RoM) and force exertion (the latter, during countermovement jumps). The results of these tests are in agreement with the existing literature [237,244] and symmetry values proved to be within physiological ranges [241]. In addition, the relatively low standard deviation values obtained for all the estimated parameters indicate that the considered population is homogeneous in terms of physiological mobility of the lower limb. Finally, excellent reliability was found in terms of the ICC value for CMJ-related parameters, confirming that the latter meet acceptable reliability standards, as previously reported by [245].

For the SLS test, the eccentric phase (from standing position to maximum knee flexion) was considered, during which an eccentric quadricep contraction and greater stress in knee structures occur. The values obtained for the acceleration and angular velocity-based parameters (RMS and peaks) appear in line with previous literature, even if a direct comparison is hard to be performed due to the differences between the considered motor tasks, experimental protocols and data processing techniques. Indeed, Pratt and Sigward quantified the shank angular velocity during single leg landing tasks and found peak values of about 200 °/s on the sagittal plane. In the present study, peak values of the shank angular velocity magnitude ranged between 51 and 75 °/s during a less impulsive task like the single leg squat.

Reliability was found to be good or excellent for all parameters except for the root mean square of the foot acceleration and the peak angular velocities of both foot and shank in the non-dominant limb. A smaller variability was indeed found in terms of reliability for the dominant limb, for which ICC values ranged from 0.60 (good) to 0.76 (excellent). This can be explained by the fact that high levels of strength and neuromuscular control are required during the eccentric phase of weight-bearing tasks as SLS [246], thus highlighting the differences between dominant and non-dominant limb. Interestingly, this between-limb difference in parameters reliability is not mirrored by the LSI results, which ranged between 95 and 112%, thus within a physiological range [241].

Remarkably, the three parameters based on the analysis of the acceleration trajectory on the coronal plane (SP, SA, and SAecc) showed good to excellent reliability for both the dominant and non-dominant limbs, proving to be good candidates for a reliable and effective quantification of the knee motion and, in turn, stability during SLS. Similar considerations can be drawn for the root mean square values of both foot and leg angular velocity (Table 21).

In the CHT, the values of the covered distance were in line with previous studies considering young healthy athletes practicing open-skills sports (football, soccer, volleyball or basketball)

[207]. The covered distance showed good to excellent reliability, proving to be a valid parameter when the test overall outcome is targeted [224]. With regards to the parameters obtained from the proposed instrumented protocol, similarly to the SLS test, a direct comparison with the existing literature is not feasible due to differences in the considered motor task and experimental protocol. However, root mean square acceleration values from 62 to 82 m/s^2 during hop landing appear to be in line with previous reported vertical acceleration peaks ranging from about 40 to 100 m/s^2 during track running [239,247]. Similarly, peak vertical angular velocity at the shank of up to 909 °/s were found during jump landing tasks [219] and are in line with the present findings, where peak magnitude angular velocity during hop landing ranged from 704 to 830 °/s.

When considering parameters reliability, temporal parameters, except the flight time, and angular velocity-based parameters showed an overall greater reliability (good to excellent) with respect to the acceleration-based counterparts. Again, even if less pronounced, greater values and consistency were found for the ICC values of the dominant limb, with respect to the non-dominant one. It is worth to underline that good to excellent reliability indicates that significant differences displayed by the considered parameter within the same participant can be ascribed to potential modifications of knee stability rather than to physiological intra-subject variability. This suggests that those parameters characterized by an ICC ranging from good to excellent can be considered as good candidates for knee stability monitoring using the proposed instrumented protocol. For those parameters showing a lower reliability, multiple measurements are warmly suggested and an average value across repetitions should be considered rather than a single measurement.

The generalizability of the present study results must be interpreted in light of the following considerations: first, data related to linear accelerations are sensitive to changes and alterations, specifically when tasks involving impacts, as the CHT, are considered. On this line, prior studies examining running tasks have observed how different running shoes and surfaces might influence the values of the acceleration components [248-250]. However, in our study the tests were carried out always on the same surface and all participants were instructed to wear standard sneakers, whose differences are assumed not to have significantly impacted the study outcome. Second, all participants were non-professional soccer players with a Tegner Level Score between 6 and 7. It can be thus assumed that the tested group was homogeneous enough to allow for a generalization of the present findings in this kind of population only, as also confirmed by the results on the CMJ and ROM. Further studies should focus on the application of the proposed protocol on athletes of different level and from other sports disciplines. Third, the relationship/correlation between some of the estimated parameters (typically the angular velocity based ones) and indicators of ACL injury risk (such as the external knee abduction moment) was already reported in the literature [219,221,240]. However, this relationship should be deeper investigated and further studies on a population of patients with ACLR is needed to strengthen and further corroborate the present findings.

CONCLUSIONS

In this second chapter an attempt to combine clinical evaluation in the sports field has been presented. In two team contact sports, such as football and basketball, new predictive indices of the ACL injury have been sought, which is the one that most affects athletes and keeps them away from the playing fields.

The case report could provide useful information for the definition of new predictive risk factors for ACL injury and synthetic indices for assessing the return to competition of injured athletes. The results indicate that the shank stability indices analyzed during the execution of the sport-specific landing gesture could be useful to identify athletes at risk of articular trauma, as well as to monitor the progress to set the return to the competition time. It will be necessary to confirm what has been described with adequate further studies in order to possibly standardize the proposed evaluation method by also assessing its repeatability.

Based on these considerations, in the second part of the chapter we implemented an observational study lasted one year with basketball players when performing monopodalic jump and single leg squat. Data gathered from experimental protocol were processed to obtain information associated with the leg stability, load absorption capability and leg mobility. We here demonstrated the good and excellent inter session reliability of some computed indices and we applied this methodology on data gathered from an athlete who suffered from ACL injury and successive reconstruction during the observational study. The outcomes of the present study led to the identification of reliable quantitative metrics that should be used as screening tools for both the assessment of athletes at higher injury risk and the evaluation of the rehabilitation program.

In the third part of the chapter, through the aim to assess the feasibility to use machine-learning algorithm for the identification of basketball players associated with a higher risk of anterior cruciate ligament injury, we compared nine different classifiers fed with data related to leg stability, leg mobility and load absorption capability. Data were gathered from thirty-nine female basketball players when performing single leg countermovement jump and sing leg squat. Landing Error Scoring System was used to identify the athletes at higher risk injury and as supervisor for the machine-learning algorithms. Results reveal as support vector machine implemented with linear kernel allowed achieving the best performance in terms of accuracy, F1-score and goodness index. By analyzing the feature importance, the ellipse area and root mean square of the acceleration measured during the jump test, as well as the angle reached during the single leg squat, showed the greatest sensitivity to discriminate if an athlete is at risk injury. In addition, the ellipse area strongly correlated with the LESS score. The obtained findings permit to validate the use of artificial intelligence approach as a predictive tool for anterior cruciate ligament injury monitor.

In the final part of the chapter the attention was shifted to football by applying a methodology similar to the previous works and placing the emphasis on the reliability of the measures, in fact, in this context the assessment of the reliability of sensor-based parameters is fundamental to set basis for the implementation of a suitable and accurate sensor-based protocol. An instrumented protocol based on tibia- and foot-mounted MIMUs during both loading and hopping motor tasks was proposed for the assessment of knee joint stability. For the single leg squat test, root mean square values of foot- and leg-based angular velocity magnitude together with parameters related to the acceleration pattern on the tibia transverse plane are suggested as reliable parameters to quantify knee stability. When the cross-over hop test is considered, temporal- and angular velocity- related parameters, like the total test duration, contact times and foot- and leg-based angular velocity magnitude peaks, displayed from good to excellent reliability and can thus be considered as promising candidates for ACL injury risk assessment.

These findings sets the basis for the application of the proposed instrumented protocol on a larger cohort of athletes with and without ACL reconstruction, with the aim of gathering information on knee stability and on the likelihood to sustain an ACL injury (preventive role) or to incur in re-injury (when embedded in RTS test batteries). In this perspective, the proposed protocol is expected to provide a significant contribution towards the definition of reliable and objective criteria for RTS clearance after ACL injury.

Related published papers and conference proceedings

- Santospagnuolo A, Boaretto D, Lalli D, Santoboni F, Nusca S, Callà B, **Molinaro L** et al. New predictive factors for anterior cruciate ligament injury in young female basketball players: a case report. *Med Sport* 2019; 72:654-62

- **L. Molinaro**, A. Santospagnuolo, M. C. Vulpiani, J. Taborri, M. Vetrano and S. Rossi, "Can the measurements of leg stability during jump landing predict and monitor anterior cruciate ligament injury? A case report of basketball player," 2020 *IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, Bari, Italy, 2020, pp. 1-6

- **Molinaro, L**.; Taborri, J.; Santospagnuolo, A.; Vetrano, M.; Vulpiani, M.C.; Rossi, S. Sensor-Based Indices for the Prediction and Monitoring of Anterior Cruciate Ligament Injury: Reliability Analysis and a Case Study in Basketball. *Sensors* 2021, 21, 5341

- Taborri, J.; **Molinaro, L**.; Santospagnuolo, A.; Vetrano, M.; Vulpiani, M.C.; Rossi, S. A Machine-Learning Approach to Measure the Anterior Cruciate Ligament Injury Risk in Female Basketball Players. *Sensors* 2021, 21, 3141

- Baldazzi, A.; **Molinaro, L**.; Taborri, J.; Margheritini, F.; Rossi, S. and Bergamini, E. Reliability of wearable sensors-based parameters for the assessment of knee stability. *Under Review*

3. RELIABILITY ANALYSIS OF TECHNOLOGIES FOR CLINICAL EVALUATION

Could the different positioning of the feet on the baropodometric platform influence the postural analysis? An assessment of reliability and repeatability

Introduction

The study of the distribution of the body load on the sole of the foot during static and walking is carried out through the baropodometric analysis which has become the most used method among sector operators [251]. By mapping the pressure of the plantar surface, it is possible to evaluate foot dysfunctions or pathologies [252]. Given the great utility of baropodometry, researchers in recent years have focused a lot on analyzing the use of pressure plates. The first works concern the comparison of different pressure, resistive or capacitive matrices, highlighting the fundamental technological aspects [253], other studies have focused on clinical evaluations of foot pathologies [254,255] and neurological and orthopedic dysfunctions [256-258]. Furthermore, in recent years, applications for the prevention of injuries in athletes have also been considered, mainly in sports such as football, running and basketball [259,260].

With the aim of collecting useful data, it has been shown how the different positioning of the feet can influence the posture of the subjects during a static exam. From this point of view, recent studies have shown how the different positioning of the feet affects the stabilometric parameters obtained with the force plates [261,262]. For example, Krewer et al. [261] highlighted how the different positions of the feet influenced parameters related to the center of gravity, such as the medio-lateral and antero-posterior displacement, by carrying out static and dynamic tests. The authors suggested the use of the self-selected foot position as it is the most realistic to reproduce a natural position. Antoniolli et al [263,264] concluded that the self-selected position is not only the most common for the baropodometric analysis but also the most comfortable for the subjects. Furthermore, the authors found no differences from other foot positions. On the contrary, Scoppa et al. [262] highlighted differences in the stabilometric parameters of the center of gravity by analyzing three different positions: self-selected position, orthostatic position with feet at 30° and feet closed-parallel. In fact, they suggested choosing the position with the closed-parallel feet for healthy subjects and possibly one of the other two positions for subjects with disabilities. Therefore, it is clear that the choice of the most appropriate position of the feet to perform the baropodometric analysis is still under discussion.

Another aspect often overlooked in the clinical routine but to be taken into consideration is associated with the reliability and repeatability of measurements. In fact, these two metrological characteristics are fundamental to avoid inappropriate clinical indications. In recent years, several studies have already been conducted, analyzing the reliability and repeatability of pressure plates, especially in dynamic activities, such as walking [265-268]. For example, Hafer et al. [265] achieved high intra- and inter-platform reliability values of peak pressure, maximum force and footprint area between two different pressure platforms during the stance phase of gait. Similar results were obtained by Izquierdo-Renau et al., [266] who investigated the intra- and inter-session reliability and repeatability of a pressure plate during walking and static tests, which were performed with the feet positioned in the auto-selected position.

However, to the best of the authors' knowledge, there are still no studies that have analyzed which foot positions guarantee the highest reliability and repeatability value of the baropodometric indices during static tasks. Therefore, the aim of this study is to identify the most reliable and repeatable foot position and then investigate whether the different foot positions affect the baropodometric indices provided by the pressure plate. These results could provide useful guidelines on which position should be adopted during clinical applications.

Materials & Methods

Participants

Eight healthy subjects (age 41 ± 14 y.o., height 172 ± 8 cm, weight 77 ± 17 kg, shoes size EU 41 ± 2) were recruited for the reliability and repeatability analysis. Participants were involved if they did not incur in any injuries in the last two years and they were free from any physical conditions that would affect the required task. All participants were initially informed about the aim of the study and they signed a written consent. Experimental procedures were in accordance with the principles declaimed in the Declaration of Helsinki.

Experimental Setup

Baropodometric pressure platform Beyond Pressure60x50 designed by Motustech (Italy, Rome) was used for the acquisition of baropodometric data (Figure 26). The platform is composed of 3.000 resistive 24k coated gold sensors arranged according to 50 rows and 60 columns for a total area of 598 x 518 mm^2. The sensitive area of each sensor is 1 x 1 cm^2. The full scale of the sensors is 150 N/cm^2 and with acquisition frequency up to 400 Hz. The matrix is connected to the PC via USB cable and interfaces with the Beyond software (version 0.9.9.9). The matrix is covered with a conductive synthetic rubber material in socaprene.

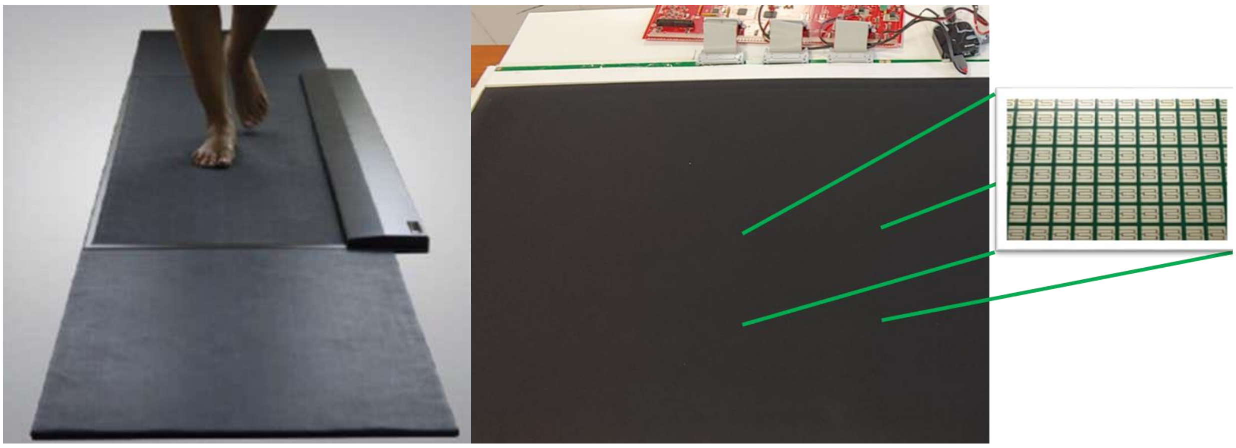


Figure 26. Pressure Platform with a zoom on the pressure matrix under the conductive cover.

Experimental Protocol

Experimental protocol consisted in a static task. Specifically, subjects were asked to take off their footwear and were instructed on the feet positions to hold during the acquisitions. The positions adopted for the analysis were four of the most used for postural and baropodometric analyses [264,265]: (i) **Self-Selected (SS):** the subject assumes the most comfortable position on the platform; (ii) **Closed-Parallel (CP):** the subject positions him/herself on the platform with the feet parallel as close as possible with metatarsals with ankles in contact; (iii) **Orthostatic (O):** the subject positions him/herself on the platform with the heels about 2 cm apart and the toes externally rotated at 30°; and, (iv) **Separated-Parallel (SP):** the subject positions him/herself on the platform with feet parallel 20 cm apart. The four positions are shown in Figure 27.

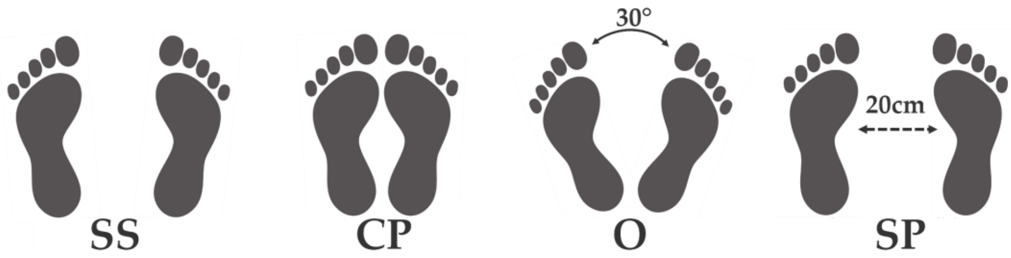


Figure 27. Feet positions: "SS" Self-Selected, "CP" Closed-Parallel, "O" Orthostatic, "SP" Separated-Parallel.

To facilitate the positioning and the correct alignment of the feet in the last three positions, reference stickers have been attached on the platform. Once the subject is positioned on the platform, with relaxed arms, he/she was instructed to look forward at a target, which was placed at 5 m, in order to stabilize the posture as much as possible. The duration of the static trial was 5 s [269]. Once the acquisition was completed, the subject step down from the platform and then repositioned himself on it. A pause of 30 s was considered between two trials. For each position, the acquisition was repeated three times and the entire experimental protocol was repeated in three different days, one week apart.

The data gathered during the three repetitions of the same day were used for the intra-day analysis, allowing to quantify the robustness of the proposed indices with respect the physiological variability; instead, the inter-day analysis was conducted on data gathered during the three different days, leading to evaluate the effects induced by both the daily change in load distribution on feet and the subject replacement on the platform. The tests were carried out in a random sequence over the three days in order to avoid bias in the results due to the same feet positions sequence.

Data Analysis

Data was acquired with a sampling rate of 50 Hz. Once the subject is positioned on the platform, the software automatically calibrates itself considering the maximum value and the weight of the subject in order to avoid saturation of the platform amplifiers. The software automatically identifies right and left foot and divided footprint in forefoot and rearfoot considering the length of the entire footprint and its different distribution of pressure, which is 60% and 40% for forefoot and rearfoot, (Figure 28). The following parameters were analyzed: (i) **the podalic angle** (PA) is the angle formed by the intersection of the two lateral tangents of the footprint (Figure 3); (ii) the **forefoot** and **rearfoot surface** (FS and RS respectively) considering the area covered by the sensors activated during the task; (iii) the **forefoot** and **rearfoot load percentage** (FL and RL, respectively) computed as the load distribution on the forefoot and rearfoot estimated from the subject weight; (iv) the **total footprint surface** (TS) considering the total area covered by the sensors activated during the task; (v) the **total load percentage**

between left and right foot (TL), indicating the percentage of the total weight distributed between the right and left side; (vi) the **ratio between the percentage of forefoot to rearfoot load** (RA) computed as the ration between FL and RL; (vii) the **maximum forefoot** and **rearfoot pressure** (PMF and PMR, respectively), which are the maximum pressure values detected by the sensors for each of the two zones; and, (viii) the **average forefoot** and **rearfoot pressure** (PAF and PAR, respectively), which are the average values of the pressures distributed on the detected surface. Each parameter was calculated for both the left and right footprint.

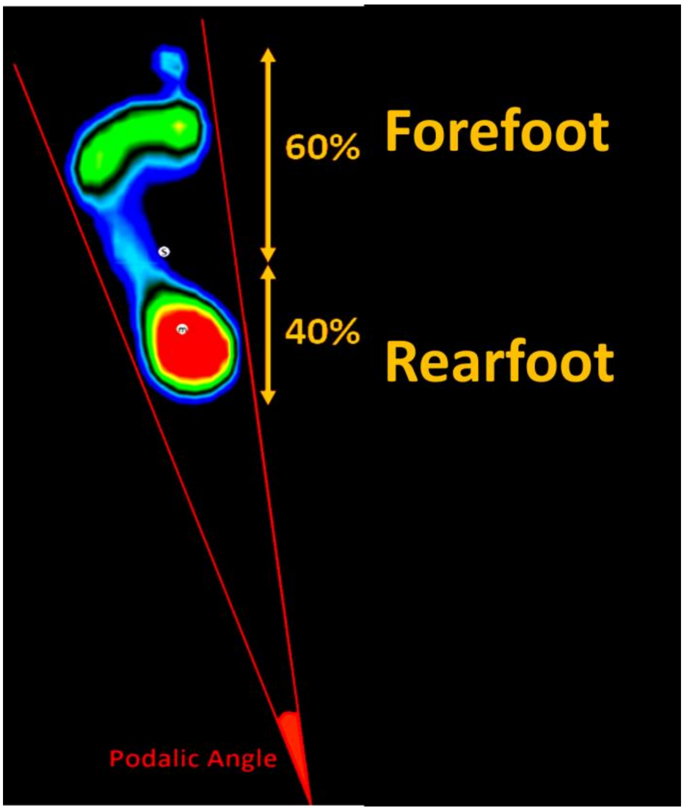


Figure 28. Subdivision of the footprint and podalic angle

Reliability and Repeatability analysis

To evaluate the intra-day reliability, ICC was computed individually for all the computed indices, for each of the three sessions and for all the feet positions. Successively, the range of ICC values was reported for each parameter and each feet position. To quantify the inter-day reliability the mean value of each parameter was firstly computed considering the three repetitions within the same day and then the ICC values were computed considering the average value for each parameter and for all the feet positions. ICC values were then discussed according the following ranges: (i) poor reliability if ICC ranged from 0.00 to 0.39; (ii) fair reliability if ICC ranged from 0.40 to 0.59; (iii) good reliability if ICC ranged from 0.60 to 0.74; and, (iv) excellent reliability if ICC ranged from 0.75 to 1.00, as reported in [38]. Focusing on intra-day repeatability, the standard deviation (SD_{intra}) of each index was calculated considering the three repetitions related to the same day; then, the mean of the SD_{intra} was calculated across the subjects. Finally, the maximum value of SD across the three session was reported as intra-day repeatability index.

For the inter-day repeatability, the standard deviation (SD_{inter}) was computed considering the mean value of each of the three sessions for all the tested indices and feet positions. The maximum value across subjects was used to quantify the inter-day repeatability.

Statistical Analysis

Data were firstly tested for normality with the Shapiro Walking test. The mean values of all the performed repetitions and sessions related to each parameter were considered to elucidate statistical differences among feet positions. Thus, a one-way repeated-measure ANOVA test was used. Bonferroni post-Hoc multiple comparison test was used to determine differences among means when ANOVA test was significant. Statistical significance was set at $p < 0.05$ for all the performed tests.

Results

Due to the similar results between dominant and non-dominant side, all the reported results are related to the dominant one. The range of the ICC values for the intra and inter-day reliability related to the parameters computed for the four positions and the standard deviations for the intra-day and the inter-day, for the same parameters, are reported in Table 22 and Table 23, respectively.

Table 22 – ICC values for the intra- and inter-day reliability for all the tested parameters and the four feet positions. Orange, gray and blue cells indicate fair, good and excellent reliability, respectively. For the intra-day, the color was decided based on the lowest value of the ICC range.

		ICC - Reliability											
		PA	**FS**	**FL**	**RS**	**RL**	**TS**	**TL**	**RA**	**PMF**	**PAF**	**PMR**	**PAR**
SS	**Intra-Day**	[0.68-0.71]	[0.90-0.93]	[0.66-0.85]	[0.96-0.97]	[0.80-0.89]	[0.95-0.97]	[0.52-0.75]	[0.76-0.89]	[0.86-0.94]	[0.75-0.89]	[0.89-0.94]	[0.86-0.90]
	Inter-Day	0.84	0.98	0.89	0.91	0.95	0.99	0.88	0.94	0.97	0.96	0.97	0.96
CP	**Intra-Day**	[0.73-0.83]	[0.86-0.94]	[0.56-0.83]	[0.91-0.97]	[0.67-0.77]	[0.95-0.97]	[0.62-0.76]	[0.67-0.85]	[0.84-0.96]	[0.81-0.91]	[0.90-0.95]	[0.81-0.92]
	Inter-Day	0.95	0.97	0.81	0.97	0.94	0.99	0.93	0.88	0.98	0.96	0.97	0.97
O	**Intra-Day**	[0.81-0.84]	[0.93-0.96]	[0.61-0.86]	[0.95-0.97]	[0.83-0.88]	[0.97-0.98]	[0.64-0.75]	[0.73-0.86]	[0.84-0.96]	[0.83-0.90]	[0.86-0.93]	[0.84-0.90]
	Inter-Day	0.96	0.99	0.95	0.94	0.98	0.99	0.96	0.96	0.99	0.97	0.96	0.96
SP	**Intra-Day**	[0.81-0.85]	[0.91-0.97]	[0.79-0.88]	[0.97-0.98]	[0.81-0.89]	[0.94-0.99]	[0.60-0.80]	[0.58-0.90]	[0.87-0.93]	[0.79-0.95]	[0.86-0.92]	[0.87-0.92]
	Inter-Day	0.96	0.97	0.79	0.97	0.89	0.99	0.89	0.82	0.91	0.97	0.93	0.94

Table 23 – Mean (SD) values for the intra- and inter-day repeatability for all the tested parameters and the four feet positions.

		Repeatability											
		PA [°]	**FS [cm²]**	**FL [%]**	**RS [cm²]**	**RL [%]**	**TS [cm²]**	**TL [%]**	**RA [%]**	**PMF [g/ cm²]**	**PAF [g/ cm²]**	**PMR [g/ cm²]**	**PAR [g/ cm²]**
SS	**Intra-Day**	9.9 (2.5)	96.0 (5.2)	25.0 (2.4)	63.8 (2.6)	25.1 (2.1)	158.5 (6.2)	50.1 (1.7)	49.9 (4.0)	549.7 (46.2)	200.1 (14.4)	682.2 (46.7)	312.7 (21.6)
	Inter-Day	10.0 (2.2)	96.3 (4.3)	25.3 (2.0)	62.8 (2.1)	25.3 (1.7)	159.0 (4.8)	50.7 (1.3)	50.1 (3.2)	537.4 (35.1)	202.7 (10.5)	682.4 (37.8)	313.7 (18.3)
CP	**Intra-**	6.0	84.4	21.7	61.8	28.2	146.8	50.0	43.5	516.5	196.0	782.2	356.6

	Day	(1.9)	(4.9)	(2.3)	(3.0)	(2.4)	(5.6)	(3.0)	(3.7)	(54.8)	(14.8)	(50.5)	(27.0)
	Inter-Day	5.9 (1.2)	85.6 (4.4)	22.2 (2.1)	62.1 (1.8)	28.3 (1.6)	147.6 (4.8)	50.5 (1.7)	44.0 (3.2)	530.7 (27.6)	200.2 (11.8)	777.3 (45.0)	352.3 (17.7)
O	**Intra-Day**	12.0 (2.7)	92.2 (4.6)	23.4 (2.2)	63.9 (3.2)	27.0 (2.0)	154.1 (4.9)	51.0 (2.5)	46.6 (3.8)	495.8 (48.8)	195.0 (11.6)	737.1 (41.7)	335.1 (20.2)
	Inter-Day	11.8 (2.1)	93.1 (3.6)	23.8 (1.5)	63.0 (2.1)	27.2 (1.2)	156.1 (5.1)	51.0 (0.9)	46.7 (2.6)	497.2 (26.2)	197.9 (9.7)	735.2 (35.8)	335.9 (15.6)
SP	**Intra-Day**	6.1 (1.6)	90.8 (5.0)	23.4 (2.4)	64.2 (2.0)	28.0 (1.5)	154.9 (6.7)	51.3 (1.5)	45.6 (3.5)	504.6 (42.8)	195.0 (12.2)	818.7 (43.4)	357.3 (21.8)
	Inter-Day	5.3 (1.0)	91.8 (5.0)	23.3 (2.0)	63.3 (1.4)	28.2 (2.0)	155.1 (5.4)	51.5 (1.2)	45.2 (3.8)	520.2 (41.0)	196.1 (8.4)	793.0 (44.1)	347.6 (22.8)

As regards the intra-day reliability, the ICC values ranged from fair to excellent. Specifically, the fair results were found in three cases, which were FL for the CP position, TL for the SS position and RA for the SP position associated with ICC equal to 0.56, 0.52 and 0.58, respectively. However, it is worth noticing that this condition was not related to all the three examined sessions, as demonstrated by the upper bound of the ICC range. In all four positions, the parameters FS, RS, TS PMF, PMR and PAR always show values in the excellent range. The remaining parameters ranged from good to excellent reliability depending on the feet positions. By focusing on the feet position, the best values for intra-day sessions have been found for O and SS. By moving to the inter-day reliability, ICC values were in the excellent range considering all parameters and all feet positions. Specifically, the lowest value was associated with the FL computed for the SP position (0.79); whereas the maximum value (0.99) was related to TS in all feet positions. The same value was achieved by FS and PMF computed for the O position. Even in the case of inter-day sessions, position O is the one with the highest ICC values, in average, followed by position SS. Table 22 also shows the results associated with the intra- and inter-day repeatability. As regards the results of the SD_{intra}, the lowest values were found for the O and SP positions.

In particular, position O showed the lowest values in parameters FS, FL, TS, PAF, PMR and PAR while position SP showed the lowest values in parameters PA, RS, RL, TL, RA and PMF. Similar results were obtained for the SD_{inter} values. In particular, position O showed the lowest values for FS, FL, RL, TL, RA, PMF, PMR and PAR while position SP showed the lowest values for PA, RS and PAF. TS showed the lowest value in the SS position.

The ANOVA results are reported in Table 24.

Table 24 – Mean (SD) for all the parameters and the four feet positions. Superscripts indicate statistical differences.

Indices	SS	CP	O	SP
PA [°]	10.0 (3.7)^{CP,SP}	5.9 (3.8)^{O,SS}	11.8 (6.6)^{SP,CP}	5.3 (3.3)^{SS,O}
FS [cm^2]	96.3 (19.5)^{CP}	85.6 (15.7)^{SS}	93.1 (20.4)	91.8 (17.9)
FL [%]	25.3 (4.2)^{CP}	22.2 (3.4)^{SS}	23.8 (4.6)	23.3 (3.0)
RS [cm^2]	66.1 (13.1)	63.0 (10.7)	66.0 (14.7)	63.5 (11.2)
RL [%]	25.3 (4.5)^{CP,SP}	28.3 (4.6)^{SS}	27.2 (5.4)	28.2 (3.8)^{SS}
TS [cm^2]	159.0	147.6	156.1	155.1

	(31.5)^{CP}	(26.7)^{SS}	(33.2)	(30.2)
TL [%]	50.7 (2.6)	50.5 (4.0)	51.0 (3.7)	51.5 (2.2)
RA [%]	50.1 (8.0)^{CP,SP}	44.0 (6.5)^{SS}	46.7 (8.8)	45.2 (6.0)^{SS}
PMF [g/ cm^2]	537.4 (141.5)	530.7 (148.1)	497.2 (152.1)	520.2 (121.5)
PAF [g/ cm^2]	202.7 (31.8)	200.2 (36.7)	197.9 (36.6)	196.1 (32.3)
PMR [g/ cm^2]	682.4 (140.6)^{CP,O,SP}	777.3 (160.0)^{SS}	735.2 (137.2)^{SS}	793.0 (127.5)^{SS}
PAR [g/ cm^2]	313.7 (55.9)^{CP,O,SP}	352.3 (68.3)	335.9 (56.2)	347.6 (63.0)

No difference among the four feet positions was found for the RS, TL, PMF and PAF parameters. In PA, differences were highlighted between SS and CP (*p* <0.01), SS and SP (*p* <0.01), CP and O (*p* <0.01) and O and SP (*p* <0.01). Differences were found between SS and CP for FS (*p* =0.03), FL (*p* =0.01) and TS (*p* =0.03). For RA and RL differences were found between SS and CP (*p* <0.01 and *p* =0.01, respectively) and SS and SP (*p* = 0.02 and *p* <0.01, respectively). For the PMR and PAR parameters, differences emerged between the SS position and all the others. For PMR between SS and CP (*p* =0.01), between SS and O (*p* <0.01) and between SS and SP (*p* <0.01), while for PAR between SS and CP *p* =0.02) between SS and O (*p* =0.05) and between SS and SP (*p* <0.01).

Discussions

The study aims at verifying which feet positions guarantees the most reliable and repeatable baropodometric indices and whether the different positioning of the feet during static tests on a pressure platform can influence the gathered synthetic indices.

Are the indices analyzed reliable and repeatable?

The reliability results allow us to assume that the indices here analyzed express a reliability from good to excellent, considering all the parameters calculated for each of the four different positions of the feet. Specifically, the parameters associated with the surface and pressure reveal themselves as the most reliable ones. These results are in line with those reported in similar works carried out on other pressure platforms and in different motor tasks, such as walking [265,266]. Although all indices are characterized by an ICC falling in the excellent range in at least one session, the use of FL, TL and RA did not ensure the achievement of reliable results due to the variability of the assessed ICC range. These results may be due to expected small physiological changes occurring in body position and muscle activity to maintain the upright, as already indicated by Izquierdo-Renaua *et al.* [266]. In particular, these changes could be more evident when considering a specific part of the foot rather than the entire load distribution. In conclusion, we can speculate that the choice of the parameters to obtain clinical indications is crucial and can influence the reliability of the outcomes. By moving to the most reliable and repeatable position, even though all evaluated foot positions show reliable indices, the orthostatic position achieved the best results. This result is already known in literature for posturographic analysis, in fact the orthostatic is the most widespread position used during the test [263]. In addition, when placing the feet in parallel configuration, an intra-rotation of the femur can occur causing a more variable maintaining of the upright position of the body [264]. The optimum results related to the SS position confirmed the literature results reported by Antoniolli *et al.*, who verified through a questionnaire that it represented the most comfortable and natural position for the subject [264]. The reported inter-day reliability permits to consider negligible the effects of both replacement of the subject on platform and intra-subject variability when performing static tasks. This is mainly due to the use of markers on the platform to indicate the correct positioning of the feet to subjects for the three constrained positions (CP, O and SP). The greater values generally found for the inter-day reliability suggest avoiding a single test in a single day to obtained reliable outcomes.

By moving to the repeatability analysis, the lowest values for almost parameters are found for the O and SP positions, proving that, they are able to provide much repeatable values, as also reported in [262,263]. Specifically, repeatability errors were always lower than 15% for all the parameters with the exception of PA. The obtained values are comparable with the ones reported by [266]. The worst value of the repeatability associated with the PA could be ascribed to the low average value that leads to an overestimation of the coefficient of variation, as assessed in [270]. The results allow to confirm the outcomes already reported in literature for walking task, also for static tasks with different feet positions. These results allow affirming that the two variability sources, which are intra-subject variability and feet repositioning, do not influence the repeatability of the proposed indices.

Are the synthetic indices influenced by feet positions?

The analysis highlighted that most differences are emerged between the SS position and the other ones. In particular, it is noted that the SS position leads to a lower load on the rear foot area that contributed to decrease the pressure on the rear foot and increase the load on the forefoot, consequently also influencing the RA, than the other positions. This effect can be a consequence of the greater comfort of the position, as already highlighted by Antoniolli *et al.* [264]. The differences confirm the outcomes reported by *Krewer et al* [261] when computing the stabilometric indices through a force platform. Further differences between the positions emerged for the PA parameter; in particular, PA for the position with parallel feet is lower than for the other two positions. This finding can be ascribed to the constrains imposed by the required position altering the morphology of the footprint and, consequently, the computation of the podalic angle. Taking into account the found differences, we can assess that the results obtained with different feet positions should not be compared since they can be affected by bias due to the position.

As a conclusion, we can speculate that baropodometric analysis should be carried out by using the orthostatic position, which guarantees the most reliable and repeatable measures. This is in line with the results in [262], in which the orthostatic position is the suggested one for clinical tests with impaired patients.

Intra and inter-day reliability of the innovative Spine3D and its ability to discriminate different postures

Introduction

The vertebral column has to protect the spinal cord, as well to support most of the body weight if considering the lumbar vertebral section [271]. Spinal abnormalities can be considered as the direct consequence of abnormal spinal alignment and wrong posture, leading to a deterioration of the life quality due to pain and reduced physical abilities in performing daily life tasks [272].

In order to customize interventions or in alternative to plan orthopedical surgery, it is mandatory a quantitative evaluation of the spinal characteristics [273]. The gold standard in the diagnosis of spinal abnormalities is still represented by the radiological examination. However, the risks associated with radiological exposure cannot be neglected also considering the necessity to monitor the progresses of the abnormalities and the effects induced by rehabilitative and/or drug treatment over the time [274]. In fact, it is well-assessed that the radiation dose received during a radiological examination can have negative long-terms effects, such as a higher incidence of cancer [275].

In the recent past, some research groups proposed the use of lower-dose solution, such as the EOS imaging system proposed by [276]; however the reduction of the cumulative effective radiation doses is limited and it is shown to be not sufficient to avoid long-term risks [277].

From this perspective, in the last decades it emerged the necessity to propose and validate radiation-free systems in order to perform noninvasive spinal abnormalities assessment. In this context, several back surface topography technologies can be listed, such as the laser scanner [278], the Moirè projection [279] and the topography based on electromagnetic [280] or ultrasound [281] waves. Among the topography-based technology, the rasterstereography is receiving particular attention by the research community. In fact, even though the radiation-free systems are not able to characterize the internal spine shape being based on the evaluation of the back surface, it is considered a viable option in comparison to the traditional radiography [282, 283]. Generally, the rasterstereography is based on the estimation of an approximate 3D image of the spine shape and its main advantages are associated with the economic and fast method without the necessity to provide radiation to the subject. For this reason, rasterstereography is widely used as tool for early screening in the detection of spinal abnormalities, especially related to the scoliosis [274], [285]. In the last decades, several instruments have been proposed for the application of rasterstereography theory, with the first one developed by Drerup and Hierholzer in the 1980s [284], [285].

Over the years, several studies have been published to establish the validity and reliability of rasterstereography approach. Krott *et al*. [286] performed a meta-analysis on the studies that evaluated the reliability and validity of static rasterstereography, leading to the outcomes of high validity level in the assessment of lumbar lordosis, thoracic kyphosis and scoliosis angle. As examples, Mohokum *et al.* [287] proposed a study to evaluate the reliability of the system to identify the kyphotic and lordotic angles, as well the trunk length and inclination. By testing 51 volunteers, authors assessed a intratester and intertester reliability greater than 0.90 for all the examined parameters. Similarly, Guidetti and colleagues [288] examined the intra- and interday reliability of spine rasterstereographic system Formetric 4D by enrolling 26 volunteers. An excellent reliability was found also in pelvic tilt and torsion, trunk imbalance and lateral deviation. Most of the studies only evaluated the static upright position with the exception of the one proposed by Michalik *et al.* [282], who estimated the feasibility to use the Formetric system also under dynamic condition, such as locomotion.

Although the Formetric (DIERS Medical Systems, Chicago, IL, United States) is the most widespread solution for the application of rasterstereography, its validity is still questioned [289-292].

To the best of authors' knowledge, it is still missing the analysis of the intra- and interday reliability of other system as alternative of the Formetric. In addition, no studies have been proposed in order to understand if the rasterstereography is able to discriminate changes in the upright position. From this perspective, this paper aims at evaluating the intra- and interday reliability of the Spine3D system, as well to understand if the system has the capability to discriminate among four different upright positions in order to simulate the validity of such system as tool for follow-up.

Materials & Methods

Participants

Nine healthy male subjects (age 30 ± 8 years, height 173 ± 5 cm, weight 73 ± 8 kg) were recruited for the experimental protocol. Participants were involved if they have not suffered back injuries in the past three years, had never been diagnosed with any back dysfunction or pathology, and they were free from any physical condition that could affect the required tasks. All participants were initially briefed on the purpose of the study and asked to sign a written consent. The experimental procedures were in accordance with the principles stated in the Declaration of Helsinki.

Experimental Setup

Data were gathered with the innovative Spine3D non-invasive three-dimensional optoelectronic detection system designed by Sensor Medica (Guidonia Montecelio, IT). The system consists of an infrared (IR) and time-of-flight (ToF) 3D RGB camera that can be positioned along a column by means of an electric motor controlled by a joystick. The camera resolution is 1920x1080 pixels at 30 fps, the depth resolution is 512x424 pixels at 30 fps and the field of view is 70° and 60°, in the horizontal and vertical direction, respectively. The operating range of measurement is from 0.5 to 4.5 m. The ToF-camera is a tool that allows estimating in real time the distance between the camera and the framed objects, measuring the time it takes for a light pulse to travel the camera-object-camera path. [293]. Thus, the system is able to reconstruct the shape of the back, according to the approach reported in [294]. The camera is connected to a PC with vertical and touch screen and interfaces with the dedicated software Spine3D (version 1.1.11.34).

Experimental Protocol

Participants were asked to remove all upper body clothing, position themselves with their back towards the camera at a distance of 110 cm with the heels aligned and lower their pants so that the intergluteal sulcus was visible. The positioning of the feet was standardized by using ad-hoc designed footprints.

Once the participant was positioned in front of the camera, with his arms relaxed, he was asked to look forward at a target, which was placed at a distance of 2 m, in order to stabilize the posture as much as possible (Figure 29).

Figure 29. Spine3D setup**.**

At this point the operator positions the camera with the joystick in order to frame the subject from the nape to the glutes. The duration of the Spine3D acquisition is 7 s. Once the acquisition is complete, the subject removes himself from the front of the camera and then repositioned himself in front of it. During the experimental protocol, four positions were tested: (i) the natural position (NP), in which the participants assumed the most comfortable position; (ii) a natural position but with a rise (NPR) of 5 mm under the right foot; (iii) Forced Inspiration (FI), in which the participant was asked to perform a maximum inspiration and to hold the breath for the entire duration of the data acquisition; and (iv) Forced Exhalation (FE), in which the participant was asked to perform a maximum exhalation and then did not breathe during the test. For each position, the acquisition was repeated three times and a break of 30 s between each repetitions was considered. The entire experimental protocol was repeated on three different days, one week apart. The different positions were performed in a random sequence over the three days to avoid bias in the results due to the same sequence.

Data Analysis

The software automatically identifies six anatomical landmarks, following the procedure reported in [295]. Specifically, the prominent vertebra (VP), i.e. the spinous process of C7, the two right (SR) and left (SL) shoulder sepsis, i.e. the midpoint between the upper profile of the shoulder and the axillary concavity, the two lumbar dimples right (DR) and left (DL), at the same time also calculates the midpoint between them (DM), and finally the prominent bone of the sacrum (SP) at the beginning of the intergluteal sulcus were identified, as in Figure 30. After the identification of the six anatomical markers, several synthetic indices related to the transversal, sagittal and frontal plane were analyzed. As regards the transversal plane, the **shoulder torsion** (ST) and the **pelvic torsion** (PT) were computed. The ST represents the angle formed on the transverse plane between SR and SL. The PT is the angle formed on the transverse plane between DL and DR. By moving to the frontal plane, we computed the t**runk length** (TL), the **trunk imbalance** (TI), the **shoulder inclination** (SI) and the **pelvic inclination** (PI). Specifically, TL is the distance between VP and DM; TI is the angle on the frontal plane between VP and DM; SI is the angle formed between SL and SR in the frontal plane; and PI is the angle formed between DL and DR in the frontal plane (Figure 31a). Finally, in the sagittal plane the **column inclination** (CI), the **cervical arrow** (CA), the **lumbar arrow** (LA), the **kyphotic angle** (KA) and the **lordotic angle** (LOA) were computed (Figure 31b and 31c). More in detail, CI is the angle formed between VP and DM in the sagittal plane; CA is the distance between the point of the cervical tract furthest from the axis perpendicular to the ground and tangent to the kyphotic curve; LA is the distance between the point of the lumbar spine furthest from the axis perpendicular to the ground and tangent to the kyphotic curve; KA is the upper angle formed by the intersection of the two tangents in the cervico-thoracic and thoraco-lumbar inversion points; and LOA is the upper angle formed by the intersection of the two tangents at the thoraco-lumbar and lumbo-sacral inversion points.

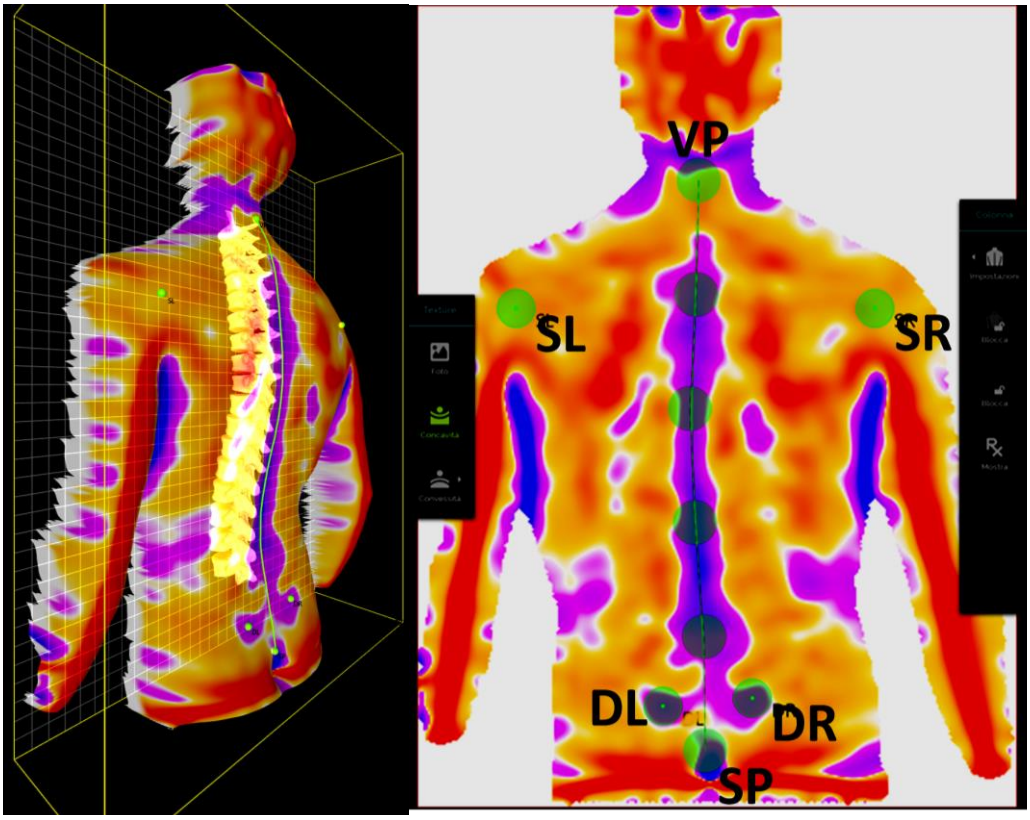
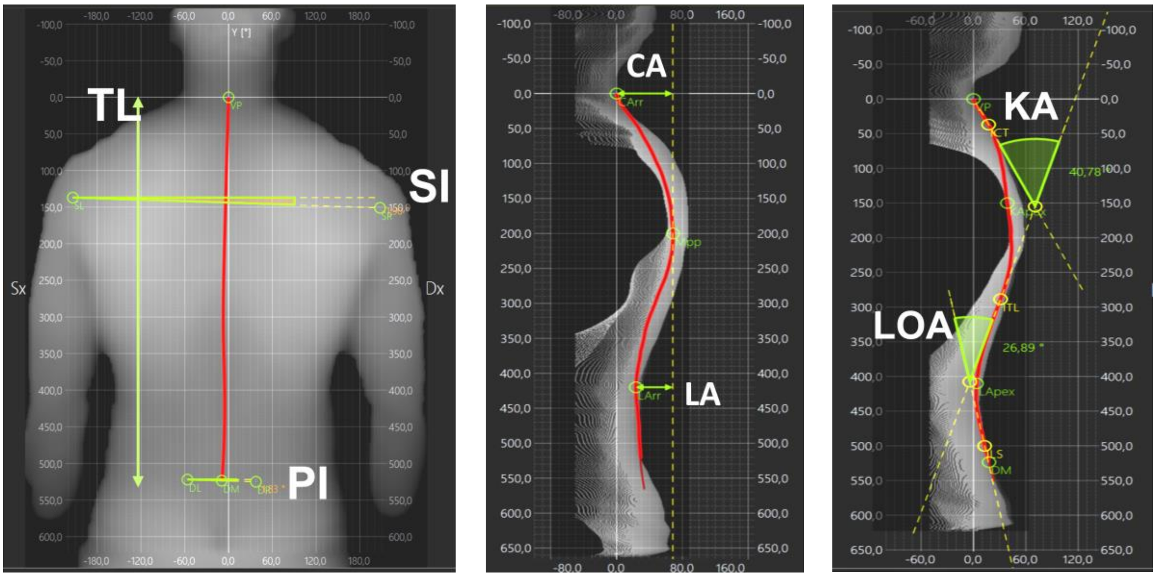


Figure 30. Landmark identification.



(a) **(b)** **(c)**

Figure 31. Definition of: (a)Trunk Length (TL), Shoulder Inclination (SI) and Pelvic Inclination (PI); (b) Cervical Arrow (CA), Lumbar Arrow (LA); and (d) Kyphotic Angle (KA) and Lordotic Angle (LOA).

Reliability Analysis

For the reliability analysis, only the data acquired during the NP tests were used since NP represents the actual position used during the clinical tests. The data collected during the three repetitions of the same day were used for the intra-day analysis, allowing to quantify the robustness of the proposed indices with respect to the physiological variability. Instead, the inter-day analysis was conducted on the data collected during the three different days, leading to the evaluation of the effects induced both by the positioning of the camera by the operator and by the replacement of the subject in front of the camera.

To evaluate the intra-day reliability of the NP, ICC was computed individually for all the computed indices and for each of the three sessions, finally, the range of ICC values was reported for each parameter. To quantify the inter-day reliability, the mean value of each parameter was firstly computed considering the three repetitions within the same day and then the ICC values were computed considering the average value for each parameter. ICC values were then discussed according to the following ranges: (i) poor reliability if ICC value is lower than 0.50; (ii) moderate reliability if ICC value is ranged from 0.50 to 0.75; good reliability if ICC value falls in the interval 0.75-0.90; and (iv) excellent reliability when ICC is equal or greater to 0.90 [296].

Effects of different positions

In order to test the effects induced by different positions and to understand if the selected synthetic indices are sensitive to these forced changes in participant’s positioning, we perform a statistical analysis as follows.

For each index, we computed the mean value across all repetitions, independently for each participant and each tested position. Data were then tested for normality with the Shapiro Walking test. Successively, paired samples T-tests were performed between the NP and the others to elucidate statistical differences among postural positions.

Statistical significance was set at $p < 0.05$ for all the performed tests.

Results

The range of the ICC values for the intra and inter-day reliability related to the parameters computed for the NP are reported in Table 25.

Table 25 – ICC values for the intra- and inter-day reliability.

Indices	Intra-day	Inter-day
ST [°]	[0.85-0.92]	0.83
PT [°]	[0.72-0.85]	0.76
TL [mm]	[0.92-0.99]	0.99
TI [°]	[0.74-0.85]	0.90
SI [°]	[0.79-0.89]	0.96
PI [°]	[0.78-0.82]	0.97
CI [°]	[0.79-0.91]	0.89
CA [mm]	[0.85-0.88]	0.96
LA [mm]	[0.86-0.94]	0.91
KA [°]	[0.76-0.81]	0.87
LOA [°]	[0.80-0.94]	0.97

Regarding intra-day reliability, ICC values range from moderate to excellent. Specifically, moderate results were found in two cases, PT and TI with an ICC equal to 0.72 and 0.74, respectively. However, it is worth noting that this condition was unrelated to all three sessions tested, as demonstrated by the upper limit of the ICC range. In all three sessions, the TL always show values in the excellent range. All the remaining parameters shows values from good to excellent range. Moving on to inter-day reliability, the parameters ST, PT, CI and KA fall into the good range 0.83, 0.76, 0.89 and 0.87 respectively, while all others are in the excellent range.

The paired samples T-test results are shown in Table 26. No difference between NP and other postures was found for the ST, PT, TI, LA and LOA parameters. The KA parameter seems to be the most sensitive to the position variation as it shows differences between the NP position and all the others, $p=0.022$, $p=0.009$ and $p=0.003$ respectively for NPR, FI and FE. Between NP and NPR there are significant differences in the parameters SI ($p=0.042$) and PI ($p=0.003$). Between NP and FI there are significant differences in the parameters TL ($p<0.001$), CI ($p=0.004$) and CA ($p<0.008$) respectively. Finally, between NP and FE there is significant difference in CA ($p<0.043$).

Table 26 – Mean (SD) for all the parameters and the four positions. Asterisks indicate statistical differences.

Indices	NP	NPR	FI	FE
ST [°]	2,1(2,1)	2,0(2)	1,6(1,6)	1,7(2,1)
PT [°]	1,0(1,9)	1,4(1,5)	1,0(1,4)	0,6(2,1)
TL [mm]	500(30,1)	500(30,2)	510(31,1)*	501(31,2)

TI [°]	0,9(0,8)	1,0(0,9)	0,9(0,9)	0,8(0,9)
SI [°]	-0,1(1,4)	0,4(1,6)*	-0,1(1,4)	-0,1(1,5)
PI [°]	1,9(4,5)	3,0(3,9)*	1,2(3,7)	2,2(3,2)
CI [°]	3,8(1,5)	4,0(1,7)	2,5(1,5)*	3,9(2,0)
CA [mm]	59(11,1)	59(11,5)	47(16,1)*	63(12,7)*
LA [mm]	40(8,7)	39(8,7)	40(8,3)	42(10,2)
KA [°]	48,1(6,5)	47,3(6,5)*	42,5(6,4)*	50,9(7,4)*
LOA [°]	34,1(8,5)	32,7(7,0)	34,6(8,0)	34,5(8,5)

Discussions

The study aimed to verify the reliability of the measures of the various indices proposed by the instrument and to verify if the instrument was able to identify differences between different postural situations.

Are the indices analyzed reliable?

The results reported for the intra- and inter-reliability are in line with those highlighted by other studies on similar parameters [296]. In particular, the TL is the most reliable parameter; similarly to the results reported by [288], [297].

The moderate level of variability found for PT and TI is in agreement with previous works. In particular, PT value is in line with the study of Manca *et al*. [298],who found range varied from 0.69 to 0.87, but also greater than those found by Guidetti *et al*. ranged from 0.42 to 0.77 [288]. Such finding can be ascribed to the evidence that PT seems to be more influenced by the positioning of the patient as already highlighted by the other authors [288]. As far as TI is concerned, the variability of this parameter is most likely given by its nature as a measure derived from the identification of DM, which in turn depends on the positioning of DL and DR. Thus, its moderate reliability can be ascribed to the algorithm used for its computation. For these reasons, the use of PT and TI as clinical index could be led in misconclusions on health status of the patient.

More in general, as a guideline, we can speculate that the higher values generally found for inter-day reliability suggest the necessity to repeat the evaluation in different days to obtain more robust results. Thus, the effects induced by the replacement of the subject in front of the camera and the adjustment of camera height performed by the operator can be considered negligible.

Can Spine3D detect changes in upright positions?

Firstly, the found average NP values and its variability are similar to those found by studies with stereophotogrammetric systems [299], allowing to consider the used methodology able to measure such parameters.

The statistical analysis detects differences between NP and the other positions for some parameters that are strictly connected with the modification applied to each position.

During FI we found a significant increase of TL and a significant decrease of CI, CA and KA values respect the NP; these changes are consistent with the well-known anatomical modification during inspiration. In fact, when a deep inhalation is performed, the rib cage expands by lowering the diaphragm, the shoulders rise and the spine extends [300]. On the other hand, during FE we have the significant increase of CA and KA is coherent with the anatomical and natural motion of the body during exhalation where the shoulders tend to go down and the head tends to move forward [300]. The use of a rise of 5mm under the right foot (NPR) shows a coherent significant modification of SI and PI and a slight but significant reduction of the KA. These modifications can be read as natural postural adaptations to manage the asymmetric rise under the foot [301]. KA confirms to be a very sensitive parameter in all the modified positions respect NP and it is consistent with the ICC values discussion. For this reason, the operators should have to pay attention at the breathing of the subjects during the acquisition process, using a normal, quiet and natural breathing. In addition, we can affirm that, being able to discriminate different upright positions, such proposed methodology can be exploited for follow-up in clinical settings.

CONCLUSIONS

This third chapter has the main purpose of investigating the reliability of two technologies for clinical evaluation the positioning of the subject, or his posture changes.

The first part quantifies the reliability and the repeatability of indices used in baropodometry in different configurations of the feet position. In addition, the differences among different feet positions were evaluated. The used baropodometric platform show from good to excellent intra-day and inter-day values of reliability and repeatability, regardless of the position of the feet used by the subject. The orthostatic position is generally the one associated with the best reliability and repeatability. The greatest differences in the data have substantially emerged between the SS position and the others, suggesting to compare data only if gathered with a standardized position of the feet.

The second part aims at investigating the intra- and inter-day reliability of the Spine3D and to determine the capability of the system to discriminate among four different upright positions in order to simulate the validity of such system as tool for follow-up. The most of indices fell in the range of good or excellent reliability in both intra- and inter-day analysis. In addition, the proposed methodology seems to be able to discriminate different positions, showing modifications of proper parameters that are linked from an anatomical and physiological point of view with the artificial changes produced in each position.

As a conclusion, the Spine3D is a reliable tool able to discriminate different positions of the spine of the subject and it can be recommended as an easy and fast way to analyze the surface shape of the spine for follow-up in clinical settings. Further studies should be conducted in order to assess the validity of the measurement by comparing the results with gold standard systems.

Related published papers and conference proceedings

- **L. Molinaro**, J. Taborri and S. Rossi, "Baropodometric analysis in different feet positions: reliability and repeatability evaluation," 2021 IEEE *International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT)*, 2021, pp. 295-300

- **L. Molinaro**, L. Russo, F. Cubelli, J. Taborri and S. Rossi, “Reliability analysis of an innovative technology for the assessment of spinal abnormalities” 2022 IEEE *International Symposium on Medical Measurements and Applications (MeMeA)*, Giardini Naxos, Italy, 2022 *submitted*

FINDINGS OF THE WORK

This PhD thesis proposed innovative protocols for the functional evaluation of movement and innovative predictive indices of injury risk of ACL in sport, as well as the reliability analysis of innovative technologies for clinical evaluation of human posture. In particular:

- A functional evaluation protocol was developed to assess the motor skills of athletes for coaching program implementation addressed to both beginner and karatekas who want to reach elite level in a specific technique.
- A functional assessment protocol was developed to assess and monitor the cognitive abilities of high-level athletes following technical karate training.
- New predictive indices have been proposed based on the analysis of the accelerations and angular velocities of a single inertial sensor through the performance of jumps and single leg squat applicable in different sports. These indices have proven to be reliable and useful for preventing injuries to young athletes.
- New machine learning algorithms were validated and implemented as predictive tools for monitoring anterior cruciate ligament injuries in order to provide clinical operators with new injury prevention tools.
- The reliability and usability of a baropodometric system has been established even with a different positioning of the subject on the platform so as to be able to propose a correct method of analysis during static baropodometry.
- The reliability of the 3D scanning system of the spinal column and the ability to discriminate different positions of the spine were evaluated, this allowed to establish reliable and sensitive indices to the variation of the trunk position useful for clinical screening.

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