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Running Head: Monopodial Stability Assessment by Inertial Device

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Monopodal Postural Stability Assessment by Wireless Inertial Measurement Units through the Fast Fourier Transform

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Abstract

Objectives: The aims of the present study were: (i) to describe the FFT multi-joint as monopodal postural stability measurement in well-trained athletes, (ii) to compare the within-subject FTT between laterality, joints and body segments, and (iii) to establish the within and between-subject relationship between joints.

Methods: Twelve national-level basketball players participated voluntarily in this investigation. The participants performed two 60-second repetitions of a monopodal stability test (one repetition with each lower limb), separated by three minutes of active recovery. All tests were recorded by four WIMU PRO™ inertial devices located on the ankle, knee, lumbar spine and thoracic spine. The main variable was total acceleration (AcelT), where the Fourier Transform (FFT) was applied.

Results: The higher instability results were found in the ankle and in the non-dominant lower limb (dominant=1.136±0.81 a.u.; non-dominant=1.169±.108 a.u.). In the body segment analysis, the greater percentage of differences ($\%_{diff}$) were shown between lumbar spine and knee in the dominant ($\%_{diff}$=-2.989%; *d*=0.87) and non-dominant lower limb ($\%_{diff}$=-3.243%; *d*=0.90). Finally, great between-subjects variability was found in all joints and body segments.

Conclusions: The described protocol is proposed for monopodal postural stability assessment, being useful to provide information about the stability of joints and the body segment between joints. Besides, a within-subject analysis is recommended and the FFT calculation will enable a linear analysis of each test.

Keywords: Balance, postural control, accelerometers, sport.

Introduction

Defined as the ability to maintain the centre of pressure of a body within the base of support with minimal postural sway through somatosensory information,.[1] the postural stability is regulated by complex neuro-physiological systems formed by the central and peripheral nervous system, the musculoskeletal system and the sensory receptors. A decrease of postural stability is the most important factor in the risk of suffering a fall in elderly people.[3,4] Also in the sports, a disturbance of this capacity has been found as an importance factor of injury. Monopodal postural stability is a test wide used to evaluate this capacity, since it has a relationship with injuries like ankle sprain[5] or anterior cruciate ligament tear.[6,7]The measuring instruments used for monopodal postural stability assessment may be kinetic, kinematic or electromyographic.[8] The kinetic instruments used are force platforms or wobble boards.[9] Kinematic devices include: video-analysis,[10] active and passive infrared marker systems,[11] electrogoniometers,[12] or laser displacement systems.[13] Finally, electromyographic analysis has been used to record the muscular activity that comes from the responses to movement alteration or postural adjustments.[14]

Advances in technology have facilitated the development of inertial measurement unit (IMU) that are composed of different sensors (accelerometers, gyroscopes, magnetometers, etc.) in the same device.[15] Most sensors that make up these devices are capable of detecting movement in their three axes (x, y, z) and orthogonal planes (vertical, antero-posterior and medio-lateral). This fact makes possible to assess stability/balance both in the centre of mass (COM) and in different joints.[8,16,17] In high performance sports, especially in team sports, IMU devices include performance tracking systems such as GPS[18] denominated by FIFA as Electronic Performance Tracking Systems (EPTS).[19] EPTS are commonly used by the team staff to control the amount of workload or effort of an athlete,[20–22] and could be useful to study of others applications as the sport rehabilitation. The approach of integrate the majority data as possible in the same system are in the line of Bucheeit et al.[23] and previous studies have addressed this approach of integrating different measures with the same system.[24,25]

The validity and reliability of these devices (IMU) to assess body stability has been compared previously with force platforms and rigid-body kinematics, obtaining very satisfactory results.[26,27] Also, the location of the inertial device is important, as the device records the acceleration of the body segment or object to which it is attached.[28] Different investigations have reported the body stability in the 4th lumbar vertebra (L4) as the most suitable location.[29,30] The placement of more than one device would be able not only to specifically assess different anatomical locations, but also to assess by body segment. Moreover, it would be possible to perform a comparative analysis in relation to subject laterality, that is defined as the lower limb used to kick a ball.

Sports science researchers recognise the importance of identifying the variables that can assess stability,[31–34] so different investigations have carried out an evaluation of postural stability by different techniques. Neville et al.[26] and Leiros-Rodriguez et al.[31] applied the Root Mean Square (*RMS*) in resultant acceleration. This variable represents the mean variance of a captured signal during a period of time. Other authors as Alberts et al.[27] and Najafi et al.[19] applied specific formulas to the degrees of displacement in the assessment of the body stability. However, the application of these formulas to the selected variable provides only one final test result, so that linear analysis of the test is impossible.

Therefore, different mathematical calculations such as entropy and the Fourier transform (FFT) have been used to analyse signal complexity. Entropy is a non-linear method for complexity assessment that analyses the regularity of a temporal data series,[35] and has been used previously for trunk stability assessment.[36] In contrast, the FFT is a linear analysis method as a function of frequency domain. This variable represents any irregular and periodic time series as a sum of regular sinusoids that have different frequencies, amplitudes and relative phases, and is able to identify different frequencies contributing to the total signal.[37] Due to its specificity, the latter method is more suitable for linear movement analysis of the recorded signal.

Therefore, the objectives were: (i) to describe the FFT multi-joint as monopodal body stability measurement in well-trained athletes, (ii) to compare the within-subject FFT between laterality, joints and body segments, and (iii) to establish the within and between-subject relationship between joints.

Methods

Participants

Twelve male national-level basketball players participated voluntarily in this research (age: 23.2±3.62 years; height: 188.81±7.81 cm; body mass: 86.16±8.32 kg). None of the participants presented any physical limitations or musculoskeletal injuries that could have affected testing. The study, which was conducted according to the Declaration of Helsinki, was approved by the Bioethics Commission of the University of Murcia (register number 2061/2018). Participants were informed of the risks and discomforts associated with testing and provided written informed consent.

A-priori power analysis on the sample size was performed through the online calculator: https://www.imim.cat/ofertadeserveis/software-public/granmo/. Accepting an alpha risk of 0.05 and a beta risk of 0.2 in a bilateral contrast, 8 subjects are required to detect a difference equal to or greater than 0.5 units. A standard deviation of 0.5 is assumed. A follow-up loss rate of 0% has been estimated due to a cross-sectional design was used.

Instruments

Anthropometric characteristics

Height was measured to the nearest 0.5 cm during a maximal inhalation using a wall-mounted stadiometer (SECA, Hamburg, Germany). Body mass was obtained with an 8-electrode segmental body composition monitor BC-601 model (TANITA, Tokyo, Japan), that has been assessed previously.[38]

Stability assessment

All repetitions performed by the participants were recorded with WIMU PRO™ inertial device (RealTrack Systems, Almeria, Spain), that contains four triaxial accelerometers that detect and measure movement using a micro-electromechanical system with an adjustable sampling frequency from 10 to 1000 Hz. In this study, the sampling frequency of the devices used was 1000 Hz. The full-scale output ranges are ±16 g, ±16 g, ±32 g and ±400 g. Each device weighs 70 g and is 81×45×16 mm in size. The light weight of the device and the test used (static) ensure that the motion of the subject was not affected during the assessment by the wearable used.

Four inertial devices were placed on each subject in the following anatomical locations: (a) ankle (on the lateral aspect of the leg, 3 cm proximally from the lateral malleolus with a vertical alignment),[33] (b) thigh (5 cm up from the patella, on the lateral side),[39] (c) lumbar spine (over the vertebra L4)[25] and (d) thoracic spine (over the interescapular line (vertebra T5-T7)).[40] At knee and ankle, the devices were located on the lateral aspect of leg in all participants.

These devices were attached to the participants with a specifically designed adhesive elastic band, except the thoracic spine device that was placed in a specially designed harness (**Figure 1**). The elastic band was additionally reinforced by adhesive tape to avoid the movement of the device during the test. The protocol to attach the devices is described in a previous research,[29,30,41] not affecting the test performance. Prior to placement, the inertial devices were manually calibrated according to the manufacturer's recommendations. Throughout this process, static bias of the raw data between inertial devices, through sensorial fusion of accelerometers, was obtained excellent reliability results (*Bias*<0.002 g; *CV*=0.2327%)[41]. The AcelT variable obtained from the inertial devices was synchronized at the start and end times prior to its subsequent analysis by the S PRO software (RealTrack Systems, Almeria, Spain) with an accuracy of 0.001 s.[41,42]

Variables

Independent variables

The IMUs placement represented the anatomical location of the IMUs during the testing. The location made it possible to analyse two variables:

- **Anatomical locations:** Acceleration detected by the IMU in each specific human body placement (tibia, thigh, lumbar spine and thoracic spine).
- **Body segments:** Differences among anatomical locations that represent the balance difference by the musculoskeletal structures of the human body (segment 1: tibia - thigh; segment 2: thigh – lumbar spine; segment 3: lumbar spine – thoracic spine).

Dependent variable

The main variable used was the acceleration magnitude, called Total Acceleration (AcelT).[44] AcelT is identified as total acceleration recorded by the 3 axes of each accelerometer: (i) product of gravity (y-axis), (ii) changes in horizontal motion (x-axis), and (iii) forces related to the rotation (z-axis) of a body segment or object to which the accelerometer is attached.[45,46] The AcelT equation is shown in **Figure 2**.

Later, the Fourier transform (FFT) was applied to the AcelT variable. The FFT is a mathematic calculation used to convert signals between time (or space) and frequency domains.[37] Specifically, FFT has the aim of decomposing a function in sinusoids of different frequency, whose sum resets the original signal, and in this way, to analyse how certain frequencies contribute to the signal.[37] The FFT is calculated using the formula shown in **Figure 3.** The SPRO™ software (RealTrack Systems, Almeria, Spain) was used to extract the inertial device data from each trial and to analyse and calculate the FFT in the AcelT variable.

Procedures

The athletes visited the laboratory twice (separated by 48 hours). The environmental conditions were similar in both sessions and maintained stable. The first time that participants visited the laboratory, a session was performed to familiarise the athletes with the experimental equipment, procedures, anthropometric and physiological assessment. During the second session, the *One-Leg Standing Balance Test* was performed twice (one repetition with each lower limb) during 60 seconds (n=20). To avoid the contaminate of the counterbalanced movements at the start of each assessment, the first 10-seconds of the 60-seconds of the total evaluation were not considered for the analysis of the test. Active rest of 3 minutes was taken between the test performances with the dominant and non-dominant lower limb.

The *One-Leg Standing Balance Test* was the protocol used in the present research. This test has been commonly used to assess trunk stability (modified by Weir et al.[43]). To start the protocol, the evaluated lower limb should be extended, while the non-evaluated lower limb should be elevated 10 cm anteriorly above the ground. The elbows should be flexed (approximately 90 degrees) and hands supported on the iliac crests. The head and the pelvis should be maintained in neutral position. The test finished when the participant: (1) did not maintain the neutral alignment of the head and the pelvis, (2) did not keep the arms on the iliac crests or (3) touched the ground with the non-evaluated lower limb (modified by Weir et al.[43]).

To assure a correct body posture during the tests, two observers were trained and gave feedback to the athletes.

Before beginning the protocols, the athletes performed a standardised warm-up of 5-min running at aerobic intensity (RPE 4-5/10), and a 15-min specific warm-up with ballistic stretching, joint mobility exercises, dynamic balance exercises and specific skills of basketball. The warm-up period was monitored in real time with S PRO™ software to verify that the devices were turned on and recording the movements of the participants. A static reliability test of raw data obtained by the inertial device accelerometers was realised before start the assessments following the protocol of Gómez-Carmona et al.[41]. When the athletes had finished this protocol, they performed 5 min of recovery running.

Statistical analysis

Before starting the analysis, the normality test for criteria assumption was performed to determine the hypothesis test model. For this, the Shapiro-Wilk test[47] was performed, showing a non-normal distribution so that non-parametric statistics were used for the analysis. Firstly, FFT of each participant was shown as mean and standard deviation ($M \pm SD$). To identify the within-subject differences in relation to laterality (dominant vs. non-dominant lower limb), joint and body segment analysed, the Wilcoxon test with percentage of differences ($\%_{diff}$) and the ranges was carried out.[48] The percentage of differences equals the absolute value of the change in value, divided by the average of the 2 numbers, all multiplied by 100. Dominant lower limb was defined as the lower limb used to kick a ball, while non-dominant lower limb was defined as the lower limb supported on the ground during the kick. To represent the magnitude of differences, Cohen's d effect size (d) interpreted with the following values were used: small (0-0.2), medium (0.2-0.5), large (>0.8).[49] Finally, to estimate the regularity of the different joints during the test, calculated by the FFT, the autocorrelation calculation was performed.[50,51] This calculation establishes the joint relationship at a specific time point with the next time point during a time series analysis. The positive correlation values indicate persistence in time, and the nearness of the value to 1 indicates the degree of robustness. Besides, the within and between-subject cross correlation was performed to analyse the relationship between joints. In addition, the time series analysis (autocorrelation and cross correlation function) included the *r* value associated to a level of measure: ≥0.1, ≥0.3, ≥0.5, ≥0.7, and ≤0.9 as very poor, marginal, moderate, strong and nearly perfect, accordingly[49]. The statistical analysis was performed with the Statistical Package for the Social Sciences (SPSS, release 24.0; SPSS Inc., Chicago IL, USA). Significance was accepted as $p<0.05$ level.

Results

Figure 3 shows the FFT dynamics in the AcelT variable recorded by each inertial device placed on the different joints both in the dominant and non-dominant lower limb. A great variability was found in the signal dynamics between dominant and non-dominant lower limb at the different joints.

The descriptive analysis of the FFT dynamics in relation to joints and laterality is shown in **Table 1**. The ankle was the most unstable joint in both lower limbs (Dominant=1.131±0.122; Non-dominant=1.141±0.172). Moreover, the non-dominant lower limb presented greater instability, except for the thoracic spine. **Table 2** shows a body segments analysis performed between the evaluated joints. The highest differences were obtained in segment number 2 (knee – lumbar spine) in the dominant ($\%_{diff}$= -2.96%; p<.001; d= -0.417) and non-dominant lower limb ($\%_{diff}$ = -2.87%; p<.001; d=-0.323). Besides, **Table 3** shows the within-subject analysis where greater differences were found between the assessed participants in each joint, except in the lumbar spine ($\%_{diff}$= 0.09; p=.565; d=0.014).

Finally, an autocorrelation analysis and a cross correlation analysis between joints were performed; the latter is shown in **Table 4.** The autocorrelations in all participants showed nearly perfect results in the different joints (r=0.99-1.00). In the within-subject cross correlation analysis between joints, the better results were found in the non-dominant lower limb respect to the dominant lower limb. Moreover, great between-subject variability was found, showing the worst relationship results between the ankle and thoracic spine locations.

Discussion

The objectives of the present research were to design a proposal to assess multi-joint monopodal postural stability during the One-Leg Standing Balance test, and its application to analyse the within-subject stability between laterality, joints and body segments, and to establish the within and between-subject relationship between joints. The main results revealed the greatest monopodal postural instability in the ankle location and in the dominant lower limb. The importance of this research should be considered as it is the first to propose multi-joint monopodal postural stability assessment through a linear method of calculation, called FFT, which is based on the signal frequency.

Differences in postural balance were found in the between-subject comparison. However, in the within-subject analysis, statistical differences at joints were found in all participants. In this analysis, percentage of differences and effect sizes were very variable among athletes. These results are contrary to those obtained by Alonso et al.[52] and Cug et al.[53] who did not find monopodal postural stability differences between the dominant and non-dominant lower limb in sedentary adults during 20-second trials assessment using a force platform as the criterion. Different causes would explain contradictory results: previous studies (Alonso et al.[52] and Cug et al.[53]) use shorter test duration. The present test is 3-times bigger (60 vs 20 seconds), fatigue can appear in the test and imbalances occurs. In addition, different positions of the evaluated lower limb were used in the test; previous studies allows 10º and 15º of knee flexion, whereas in the present study, leg should be extended and a tight postural control might occur. Moreover, Cug et al. [53] permit participants to see their COM movements in the screen in real time, and control and adjust of COM sway is easily detected. In present study, a new metric is used for first time, FTT. Results suggests that this metric is more sensitive to changes that stability index. Alonso et al.[52] and Cug et al.[53] used a force platform that record only the result of the cumulative imbalances in the foot sole, allowing all the joints to smooth the imbalances that occur along the body. In the present study different devices in different locations are used, making the balance assessment much more sensitive and specific. Finally, previous studies have stated that the athletes that used in a repetitive asymmetrical activities could affect the balance pattern in single foot evaluations.[54] In fact, is have been proved that, in sports as football, where kicks with one leg are used, superior balance performance of non-dominant leg have been shown.[55] Sample of the present study are from a basketball team, where jumps with one leg occurs repetitively during a game. For these reasons, the multi-joint analysis showed differences in joint coordination patterns and body segments analysed. Therefore, the differences should be corrected individually through the application of unique training protocols independently from the rest of the teammates.

In the present research, the greatest monopodal postural instability was found in the ankle location in relation to the rest of the joints, revealing diferent postural stability values in the lumbar spine and thoracic spine locations of the trunk than those obtained by Leiros-Rodriguez et al.[30]. Most investigations analysed in this topic have assessed monopodal postural stability in one joint, such as the vertebrae L5[16] and L4[31] found no differences between them. Better results found in this study can be explained by the age of the sample.[56] Normal ageing is associate with less postural stability and each individual have had unique anatomical or functional differences. For this reason, a complete assessment of monopodal postural stability has to be individualize, measuring all the joints and the relationship between then.

Interpreting the uni-segmental differences of stability deficit in one of the joints may relate to changes that could occur up or down the kinetic chain, with the injury risk that this aspect entails.[57] Researchers have found a relationship between stability and injury risk in football[58,59] and basketball[60]. Stability and balance training are linked with a minor incidence of knee and ankle injuries.[57] Research on balance has mainly focused on an analysis of the dynamics of the human COM.[31,61,62]. Autocorrelation and cross correlation dynamic time-related analysis show great between-subject variability, complementing the simple analysis of COM. In this analysis, it has been shown that the non-dominant lower limb presents better results. This could be due to the fact that, in sportspeople, this is the strong lower limb and it has a stabilising function.[63] Moreover, it has been demonstrated that loss of strength is an important predictor of balance and stability in healthy people.[31] Accordingly, it would be necessary to include strength training in stability and balance training programmes. An effective and specific assessment of the joints deficits and dynamics time related analysis that contribute to stability will help in the prescription and planning of better individualised training programmes for each subject evaluated.

Limitations

Some limitations of the present study should be considered when interpreting the findings. Firstly, the number of participants was small (n = 12), but with an enough statistical power to the results reported. Besides, the participants were specialised athletes (national-level basketball players) and were assessed with the specific and regular sport shoes used in official games and training sessions. These findings cannot be extrapolated to another population; however, the efficacy of this protocol should be investigated in future studies at other applications as the assessment of fall risk in elderly population. Finally, only four WIMU PRO^{TM} inertial devices at a specific sampling rate were tested. Both the sensor components within the IMU, the calibration of the sensors, and the sampling rate could have an effect on the results. All processes were carried out following the manufacturer's recommendations. Accordingly, future research should follow the protocol described in the present study with the objective of extrapolating the application of the obtained results to different populations or sports modalities.

Conclusions

In the analysed participants, laterality differences were found in all cases. Non-dominant leg was reported the major monopodal postural instability measurement, excepting at lumbar spine, where the results between dominant and non-dominant lower limb were inconsistent. This fact is due to the centre of mass of human body is located at lumbar spine and intervenes in the regulation of balance in both lower limbs. The major monopodal postural stability was found in thoracic spine, while the major monopodal postural instability joint was found at the ankle of non-dominant lower limb. Nonetheless, several cases were in contrast of this monopodal postural stability pattern, so these findings should be considered with caution due to an individual monopodal postural stability pattern was found. The individualize stability development of each participant could be produced by previous injuries, training model, sport career and maturate development, among others. Finally, the higher differences in monopodal postural stability at body segments was found between ankle and lumbar spine due to in this location the postural stability change between upper and lower limb occurs. For all this, it is necessary a within-subject comparison, so from objective and individual information about an athlete, specific training programs and return-to-play processes must be designed.

Practical Applications and Future Research

Given the obtained results, we propose multi-joint monopodal postural stability assessment using the protocol described in the present study. Thanks to this, it will allow managing information on each joint and body segment between joints by the evaluator. Moreover, the use of the FFT calculation will enable a linear analysis of the test, providing continuous assessment throughout the protocol. With this proposal, is possible to identify the joint or specific body segment where a postural stability deficit is found. Currently, that would be impossible with the established protocols, where only one joint is assessed. Finally, future research must use this standardized protocol with linear analysis along the test to identify and establish the multi-joint individual balance learning curve of each athlete during a longitudinal study design with repeated measures, being related to real sport context.

Conflict of interest disclosure

Removed in blinding process

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Removed in blinding process

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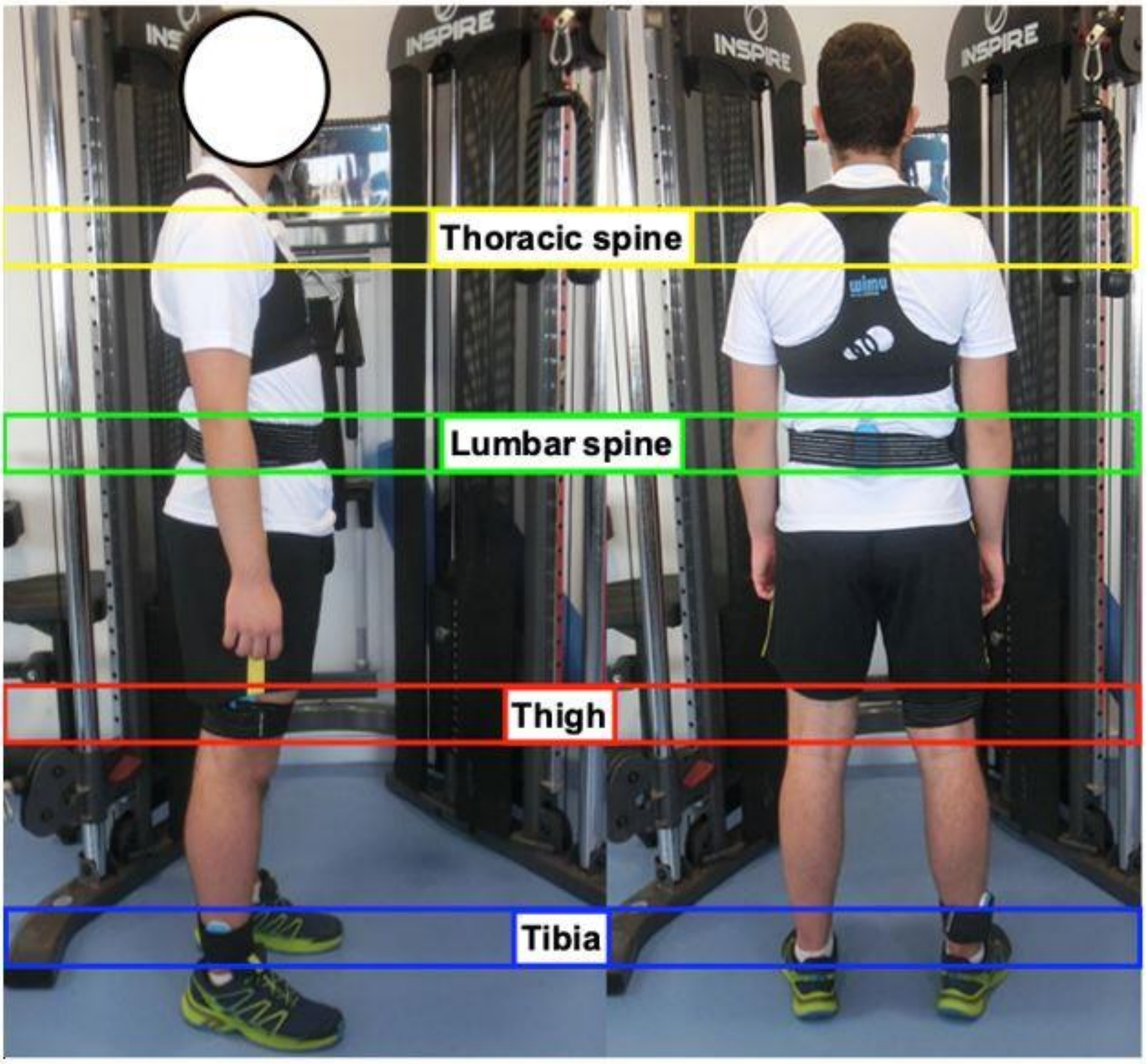

Figure 1. WIMU PRO^{TM} inertial device location during the protocol analysed in the present study.

$$Resultant\ vector\ (AcelT) = \sqrt{x^2 + y^2 + z^2}$$

Figure 2. Resultant vector of 3-axis acceleration (AcelT). where: z, antero-posterior acceleration; x, mid-lateral acceleration; y, vertical acceleration.

$$\mathbb{F}[f(t)] = F(\omega) = \int_{-\infty}^{\infty} f(t).\ e^{-j\omega t}\,\partial t$$

$$\mathbb{F}^{-1}[F(\omega)] = f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega).\ e^{+j\omega t}\,\partial\omega$$

Figure 3. Fourier Transform (FFT) formula, where (t) time, (ω) angular frequency, (F) or (f) frequency, (π) pi, (∫) integral, (∂) partial derivative, (e) Euler number, and (j) entire parameter.

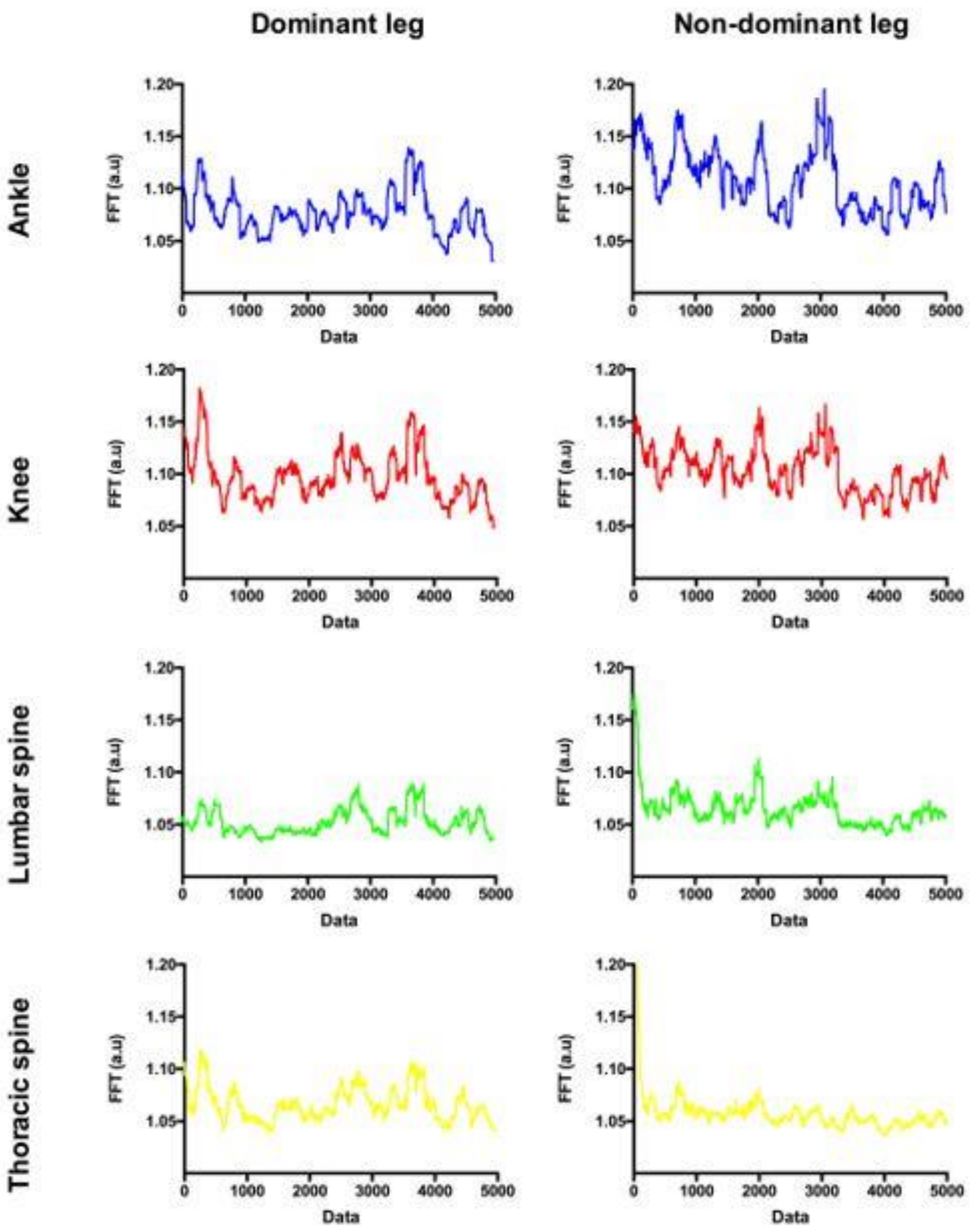

Figure 4. Representation of the Fourier Transform (FFT) dynamics calculated in AcelT signal during a 60-second One-Leg Standing Balance test, that is recorded by four WIMU PRO^{TM} inertial devices at a sampling frequency of 1000 Hz, with the dominant and non-dominant lower limb, on the four anatomical locations analysed: (a) ankle, (b) knee, (c) lumbar spine and (d) thoracic spine.

"Monopodal Postural Stability Assessment by Wireless Inertial Measurement Units through the Fast Fourier Transform"
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Table 1. Descriptive analysis of FFT dynamics during the One-Leg Standing Balance test in relation to laterality and joint where WIMU PRO^{TM} inertial devices were placed.

	Dominant lower limb								Non-Dominant lower limb							
Participant	Tibia		Thigh		Lumbar spine		Thoracic spine		Tibia		Thigh		Lumbar spine		Thoracic spine	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
1	1.195	0.089	1.125	0.065	1.103	0.043	1.082	0.046	1.217	0.401	1.214	0.311	1.150	0.135	1.127	0.113
2	1.097	0.040	1.138	0.059	1.085	0.039	1.079	0.035	1.140	0.061	1.154	0.079	1.109	0.056	1.086	0.043
3	1.113	0.116	1.097	0.045	1.075	0.090	1.080	0.130	1.263	0.244	1.126	0.059	1.074	0.090	1.067	0.131
4	1.123	0.121	1.121	0.059	1.088	0.092	1.095	0.132	1.169	0.164	1.101	0.069	1.068	0.098	1.069	0.136
5	1.117	0.025	1.129	0.020	1.065	0.013	1.055	0.008	1.089	0.017	1.088	0.016	1.063	0.012	1.063	0.013
6	1.073	0.119	1.077	0.047	1.065	0.091	1.058	0.131	1.099	0.120	1.084	0.045	1.074	0.090	1.070	0.132
7	1.092	0.081	1.112	0.054	1.060	0.026	1.073	0.029	1.106	0.028	1.102	0.022	1.063	0.017	1.057	0.021
8	1.254	0.182	1.105	0.049	1.068	0.027	1.069	0.027	1.143	0.131	1.148	0.116	1.094	0.037	1.086	0.036
9	1.105	0.036	1.110	0.043	1.083	0.041	1.087	0.058	1.195	0.089	1.125	0.065	1.103	0.043	1.082	0.046
10	1.117	0.024	1.130	0.020	1.066	0.013	1.055	0.008	1.090	0.017	1.088	0.016	1.063	0.012	1.063	0.013
11	1.213	0.184	1.161	0.232	1.143	0.091	1.107	0.067	1.060	0.015	1.070	0.023	1.067	0.021	1.051	0.015
12	1.109	0.127	1.088	0.054	1.085	0.092	1.070	0.130	1.099	0.121	1.073	0.051	1.060	0.091	1.058	0.132
Total	1.131	0.122	1.114	0.082	1.082	0.070	1.076	0.090	1.141	0.172	1.112	0.109	1.081	0.077	1.072	0.095

Note. *M: Mean; SD: Standard deviation.*

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Table 2. Within-subject differences of related samples. Percentage of differences, p value, ranges and Cohen's d effect size on FFT dynamics in relation to body segments during the One-Leg Standing Balance test in dominant and non-dominant lower limb trials.

Laterality	Participants	Segment 1: Thigh - Tibia				Segment 2: Lumbar spine - Thigh				Segment 3: Thoracic spine – Lumbar spine			
		$\%_{diff}$	*p*	Ranges (ti-th-d)	*d*	$\%_{diff}$	*p*	Ranges (th-ls-d)	*d*	$\%_{diff}$	*p*	Ranges (ls-ts-d)	*d*
Dominant	1	-6.22	.000	5791-209-0	-0.912	-1.99	.000	4929-1071-0	-0.392	-1.94	.000	5466-534-0	-0.230
	2	3.60	.000	0-6000-0	0.799	-4.88	.000	5642-358-0	-1.040	-0.56	.000	4288-1712-0	-0.080
	3	-1.46	.000	5017-3379-0	-0.189	-2.05	.000	7991-405-0	-0.319	0.46	.042	4128-4268-0	0.023
	4	-0.18	.000	3259-5018-0	-0.022	-3.03	.000	7918-359-0	-0.436	0.64	.000	3564-4713-0	0.031
	5	1.06	.000	1642-4356-0	-0.536	-6.01	.000	5998-0-0	-3.722	-0.95	.000	5201-797-0	-0.413
	6	0.37	.000	1460-6815-0	0.046	-1.13	.000	7695-580-0	-0.171	-0.66	.000	7616-659-0	-0.032
	7	1.80	.000	350-5650-0	0.296	-4.91	.000	5959-41-0	-1.192	1.21	.000	504-5496-0	0.231
	8	-13.48	.000	3807-2191-0	-1.168	-3.46	.000	5810-188-0	-0.912	0.09	.000	2954-3044-0	0.019
	9	0.45	.000	2359-3641-0	0.125	-2.49	.000	5189-811-0	-0.641	0.37	.002	3133-2867-0	0.040
	10	1.15	.000	1609-4391-0	0.594	-6.00	.000	6000-0-0	-3.722	-1.04	.000	5286-714-0	-0.446
	11	-4.48	.000	4329-1669-0	-0.246	-1.57	.000	3616-2382-0	-0.099	-3.25	.000	5134-864-0	-0.217
	12	-1.93	.000	5740-2926-0	-0.223	-0.28	.000	6011-2385-0	-0.041	-1.40	.000	7932-464-0	-0.068
	Total	-1.53	.000	35093-46245-0	-0.167	-2.96	.000	71524-9814-0	-0.417	-0.56	.000	55206-26132-0	-0.038
Non-Dominant	1	-0.25	.000	1305-4965-0	-0.008	-5.57	.000	4825-1175-0	-0.259	-2.04	.000	5052-948-0	-0.183
	2	1.21	.000	2015-3985-0	0.201	-4.06	.000	5810-190-0	-0.647	-2.12	.000	5523-477-0	-0.455
	3	-12.17	.000	5582-2814-0	-0.741	-4.84	.000	8267-129-0	-0.697	-0.66	.000	7168-1228-0	-0.063
	4	-6.18	.000	5971-2306-0	-0.523	-3.09	.000	8128-149-0	-0.396	0.09	.000	5823-2454-0	0.009
	5	-0.09	.000	3435-2563-0	-0.060	-2.35	.000	5983-15-0	-1.744	0.00	.059	3077-2921-0	0.000
	6	-1.38	.000	4960-3315-0	-0.160	-0.93	.000	7547-728-0	-0.145	-0.37	.000	7083-1192-0	-0.036
	7	-0.36	.000	3775-2225-0	-0.157	-3.67	.000	5919-81-0	-1.960	-0.57	.000	4456-1544-0	-0.317
	8	0.44	.000	2555-3443-0	0.040	-4.94	.000	5593-405-0	-0.604	-0.74	.000	4441-1557-0	-0.219
	9	-6.22	.000	5791-209-0	-0.885	-1.99	.000	4929-1071-0	-0.392	-1.94	.000	5466-534-0	-0.473
	10	-0.18	.000	3510-2490-0	-0.121	-2.35	.000	5985-15-0	-1.744	0.00	.043	3082-2918-0	0.000

Laterality	Participants	Segment 1: Thigh - Tibia				Segment 2: Lumbar spine - Thigh				Segment 3: Thoracic spine – Lumbar spine			
		$\%_{diff}$	*p*	Ranges (ti-th-d)	*d*	$\%_{diff}$	*p*	Ranges (th-ls-d)	*d*	$\%_{diff}$	*p*	Ranges (ls-ts-d)	*d*
	11	0.93	.000	1399-4599-0	0.525	-0.28	.000	3518-2417-0	-0.136	-1.52	.000	5789-209-0	-0.863
	12	-2.42	.000	7620-776-0	-0.271	-1.23	.000	7766-630-0	-0.181	-0.19	.000	7341-1055-0	-0.018
	Total	-2.61	.000	47918-33420-0	-0.197	-2.87	.000	74333-7005-0	-0.323	-0.84	.000	64301-17037-0	-0.105

Note. *$\%_{diff}$: Percentage of differences; p: p value; Ranges (ti: tibia, th: thigh, ls: lumbar spine, ts: thoracic spine, d: draws); d: Cohen's d effect size*

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Table 3. Within-subject differences of related samples. Percentage of differences, p value, ranges and Cohen’s d effect size on FFT dynamics in relation to laterality during the One-Leg Standing Balance test.

Subject	Tibia				Thigh				Lumbar spine				Thoracic spine			
	$\%_{diff}$	*p*	Ranges (dl-ndl-d)	*d*	$\%_{diff}$	*p*	Ranges (dl-ndl-d)	*d*	$\%_{diff}$	*p*	Ranges (dl-ndl-d)	*d*	$\%_{diff}$	*p*	Ranges (dl-ndl-d)	*d*
1	-1.81	.000	4399-1601-0	-0.073	-7.33	.000	2487-3513-0	-0.380	-4.09	.000	2533-3467-0	-0.452	-3.99	.000	2118-3882-0	-0.245
2	-3.77	.000	1176-4824-0	-0.818	-1.39	.000	2237-3763-0	-0.226	-2.16	.000	1242-4758-0	-0.489	-0.64	.000	2183-3817-0	-0.088
3	-11.88	.000	2260-6136-0	-0.762	-2.58	.000	2373-6024-0	-0.546	0.09	.000	4473-3923-0	0.011	1.22	.000	6138-2258-0	0.050
4	-3.93	.000	3076-5201-0	-0.315	1.82	.000	5179-3098-0	0.309	1.87	.000	5591-2686-0	0.210	2.43	.000	6290-1987-0	0.096
5	2.57	.000	4660-1338-0	1.334	3.77	.000	5792-206-0	2.288	0.19	.000	2949-3049-0	0.160	-0.75	.000	1642-4356-0	-0.341
6	-2.37	.000	2912-6083-0	-0.217	-0.65	.000	3670-4605-0	-0.152	-0.84	.000	2977-5298-0	-0.099	-1.12	.000	2331-5944-0	-0.046
7	-1.27	.000	1326-4674-0	-0.240	0.91	.000	2867-3133-0	0.251	-0.28	.000	2284-3716-0	-0.139	1.51	.000	4438-1562-0	0.306
8	9.71	.000	3913-2085-0	0.711	-3.75	.000	1725-4237-0	-0.467	-2.38	.000	1215-4783-0	-0.791	-1.57	.000	1720-4287-0	-0.255
9	-7.53	.000	554-5446-0	-1.282	-1.33	.000	2380-3620-0	-0.267	-1.81	.000	1492-4508-0	-0.475	0.46	.000	2621-3379-0	0.048
10	2.48	.000	4961-1039-0	1.320	3.86	.000	5570-430-0	2.344	0.28	.000	3510-2490-0	0.241	-0.75	.000	1581-4419-0	-0.341
11	14.43	.000	5234-764-0	1.232	8.50	.000	4584-1414-0	0.580	7.12	.000	4767-1231-0	1.204	5.33	.000	4591-1407-0	0.517
12	0.91	.000	5005-3391-0	0.081	1.40	.000	5782-2614-0	0.286	2.36	.000	6597-1799-0	0.273	1.13	.000	5949-2447-0	0.046
Total	-0.88	.000	38756-42582-0	-0.066	0.18	.000	44645-36693-0	0.020	0.09	.565	39630-41708-0	0.014	0.37	.000	41602-39736-0	0.022

Note. *$\%_{diff}$: Percentage of differences; p: p value; Ranges (ndl: non-dominant leg , dl: dominant leg, d: draws); d: Cohen’s d effect size*

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Table 4. Between-joint and within-subject cross correlations in the FFT dynamics.

Location		1		2		3		4		5		6		7		8		9		10		11		12		Total	
		ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D
Tibia	Thigh	.77	.23	.45	-.18	.89	.84	.79	.73	.80	.79	.79	.48	.76	.49	.93	.96	.90	.91	.51	.87	.64	.80	.90	.84	.68	.42
	LS	.69	.40	.69	.01	.67	.64	.67	.62	.74	.67	.55	.50	.58	.51	.80	.80	.98	.99	.49	.97	.69	.96	.99	.92	.66	.68
	TS	.72	.48	.79	-.09	.45	.67	.61	.44	.73	.61	.68	.64	.66	.65	.71	.85	.97	.99	.47	.98	.69	.96	.98	.93	.61	.67
Thigh	LS	.84	.44	.55	.81	.74	.74	.85	.75	.88	.85	.71	.70	.71	.71	.91	.74	.88	.93	.68	.88	.91	.77	.86	.93	.73	.56
	TS	.85	.48	.44	.85	.50	.86	.81	.59	.92	.81	.81	.59	.81	.62	.81	.78	.84	.90	.61	.85	.88	.71	.81	.88	.59	.48
LS	TS	.89	.88	.86	.88	.82	.89	.88	.92	.95	.88	.62	.73	.62	.74	.95	.95	.99	.99	.99	.99	.99	.98	.99	.98	.95	.94

Note. *LS: Lumbar spine (L3-L4); TS: Thoracic spine (interscapular line); ND: Non-dominant leg; D: Dominant leg.*

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