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RESEARCH

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How does fatigue affect handstand balance? a non-linear approach to study fatigue influence in handstand performance

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Abstract

Background The handstand is an essential skill in acrobatic sports. This skill requires the athlete to maintain an inverted upright stance with only the hands supported, which requires a great effort of muscular coordination and motor control. Several factors influence the ability to control the posture, including fatigue, which is a bit studied constraint of handstand performance.

Research question With the aim to find out whether variability in movement control can be an indicator of fatigue, the present study was carried out.

Method Fourteen male acrobatic gymnasts were required to perform handstands. The time series for analyzing variability were capturing using Force Platforms, which is a traditional laboratory instrument, and Inertial Measurement Units (IMU), which is a more recent and less widely used, but more accessible tool. For this purpose, an analysis of the amount of variability was carried out, using the standard deviation. And analysis of the structure of variability (or complexity), using Detrended Fluctuation Analysis (DFA) and Fuzzy Entropy (FuEn).

Results Our results reveal that fatigue causes significant increases in the amount of variability in the medio-lateral axis on the force platform, and in the IMU located in the area of the L5 vertebra. These changes are accompanied by increased auto-correlation in the medio-lateral axis of the force platform, and more unpredictable behavior in the L5 IMU.

Key points

- Amount of variability can discriminate between non-fatigued and fatigued states in force platform.
- Structure of variability can discriminate between non-fatigued and fatigued states in force platform.
- Movements are most affected in the medio-lateral axis.
- Forces produced to maintain balance exhibit smoother adjustments in fatigue state.
- Acceleration in the L5 tends to be less predictable in fatigue state.

Keywords Variability, Complexity, Balance, Motor Control, Gymnastic skills

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Introduction

Handstand task is defined as the action of maintaining the body in an inverted vertical stance with the hands in contact with the support surface [55]. Handstand is one of the most important skills in acrobatic sports [28]. Correct execution of a handstand implies a body position with a straight back and legs to maintain posture enduringly [52], trying to maintain the Centre of Mass (COM) vertical projection within the support area created by hands [53].

To execute the handstand, the performer realizes minimal changes in hand pressure and limb actions to control the balance position. The ability to maintain an inverted posture as the handstand requires complex muscle coordination and a high motor control of many degrees of freedom [55]. Several neurophysiological and biomechanical control processes are key to the performance of successful handstand performance [53]. Research studies about biomechanics and motor control in the handstand have been center on individual or coordinated structures, for example, the control in several joints such as hips, shoulders, or wrists [48]. Nevertheless, the role of macroscopic variables as the center of pressure (COP) has been less studied in opposite to upright balance studies where is a common variable.

Human motor control is characterized by complex nonlinear dynamics, where a multitude of constraints influence performance. In the case of handstand, different variables have been studied to know their influence on motor control of that skill. Some of those variables are performer experience [53, 55], visual availability [50], suit characteristics [15] or the surface where handstand is executed [3]. One key performance variable is upper limb strength [28] because the antigravitational function is not proper for those muscles. This function requires great muscle activity of the upper extremities [33], so those muscles succumb early to fatigue [28]. Fatigue is an important constraint in acrobatic sports because affects several aspects (biomechanical response, perception, injury tolerance, etc.) during training and competition [6, 40]. Nevertheless, to the best of the authors' knowledge, no study has analyzed the influence of fatigue on handstand performance.

The study of the relationship between fatigue and motor control has been extended in the last years, in the health field [11, 26] as many as sports performance field [2, 29]. An important number of articles about fatigue have studied its influence on upright balance [16, 19, 27]. Most of those studies found an increase in variables such as COP area and velocity displacement after fatigue conditions [12, 39]. In addition to these variables, nonlinear analysis of balance control has been considered during balance tasks [4, 13, 31]. Several authors have exposed the utility of nonlinear tools as entropy or detrend fluctuation analysis (DFA), to obtain different information during balance tasks [8]. So, while entropy analysis can assess the regularity of COP during balance tasks [51], DFA analysis can support information about the complexity of COP signal [9]. Recently these tools have been proposed such as variables sensitive to fatigue in different tasks [24]. Generally, the analysis of movement variability, whether for the detection of fatigue or other sub-optimal states of the body, has been performed using expensive and difficult to access instruments such as force and isokinetic platforms, which limits its applicability in clinical and sporting contexts [13, 31, 47]. Therefore, the present study is exploratory in nature, with the aim of evaluating the usefulness of movement variability analysis using IMU, seeking a more accessible and practical alternative.

The purpose of the present study was to investigate the influence of the fatigue process on handstand performance comparing the information from linear and non-linear analysis. We hypothesized that while COP Area and Velocity increase with fatigue, a lower irregularity and higher autocorrelation from COP signal will be observed during handstand performance.

Methods

Participants

Fourteen ($n = 14$) male acrobatic gymnasts were recruited for this study. The participants were aged 25.77 ± 5.82 years (mean ± SD), with a mass of 69.66 ± 8.78 kg and a height of 1.74 ± 0.09 m. G*Power software version 3.1.9.4 [21] was used to decide the sample size. Based on previous studies we expected fatigue to have a high effect size (at least $dz = 0.80$) [16, 50]. And it was set to expect a statistical power of 80%. Based on these parameters the sample should be at least 12 participants. No participants had any history of nervous system or muscular dysfunction at the time of measurements. Written informed consent was obtained from each participant before the experiment. The study was following the Declaration of Helsinki and was approved by a University Office for Research Ethics Testing protocol (DCD.RSS.02.19).

Experimental procedure

To preserve the integrity of the research process, all the tests were carried out in the same morning hour. The measurements were carried out in a laboratory room, in conditions that ensure the isolation of acoustic or visual stimuli that could interfere with postural control during the study. Athletes were wearing gymnastic costumes without shoes.

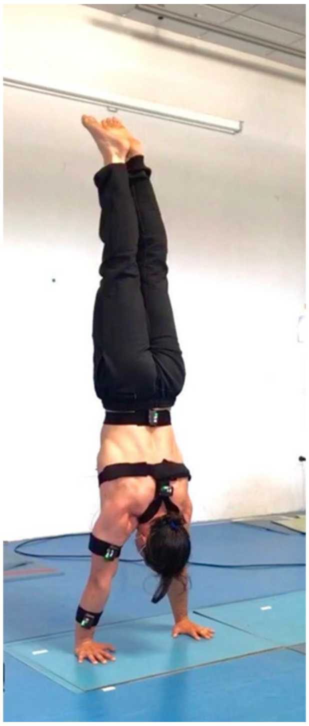

Fig. 1 Shows the set where the measurements were performed, showing the four IMUs and the force platform

To assess postural stability during the handstand task, ground reaction forces were recorded by a force platform (Kistler, Switzerland, Model 9287BA) and four IMUs (STT-System, Spain). Two IMUs were mounted on the forearm and arm from the dominant limb, and the other two near the seventh cervical vertebra (C7) and the fifth lumbar vertebra (L5). Figure 1 shows the arrangement of the devices.

After a 15-min warm-up with general movements and specific exercises for the handstand task (including 10 trials of swinging up to the handstand to familiarize themselves with the task and conditions in the lab), participants performed two 30-s trials separated by a fatigue procedure. Three minutes after the pre-test trial, two sets of 15 push-ups at a preferred velocity were done with a rest of one minute between both sets. Later the two sets of push-ups to induce fatigue the post-test trial was measured. For a schematic overview of the procedure see Fig. 2.

The participant performed a handstand with a rebound of one leg and a swing of the other leg. Stability measurement was recorded when the lower limbs were joined in a vertical position. A trigger in force plate recording was included when the participant was in vertical position. Participants were asked to stand "as still as possible" during the test. Participants must maintain balance in the handstand by using the wrist strategy and not another one (e.g., the hip or elbow strategy) which means the control was reached by movements in the wrist joint [32].

Data analysis and reduction

We collected 30 s of data at 100 Hz with a force plate and IMUs, but the first 5 s and last 5 s of each trial were discarded to avoid nonstationary signal [54]. The signal was subsampled at 50 Hz. So, the length of time series analyzed was 1000 data points. No filtering was performed on the data because filtering could affect the nonlinear results [34]. Postural performance was

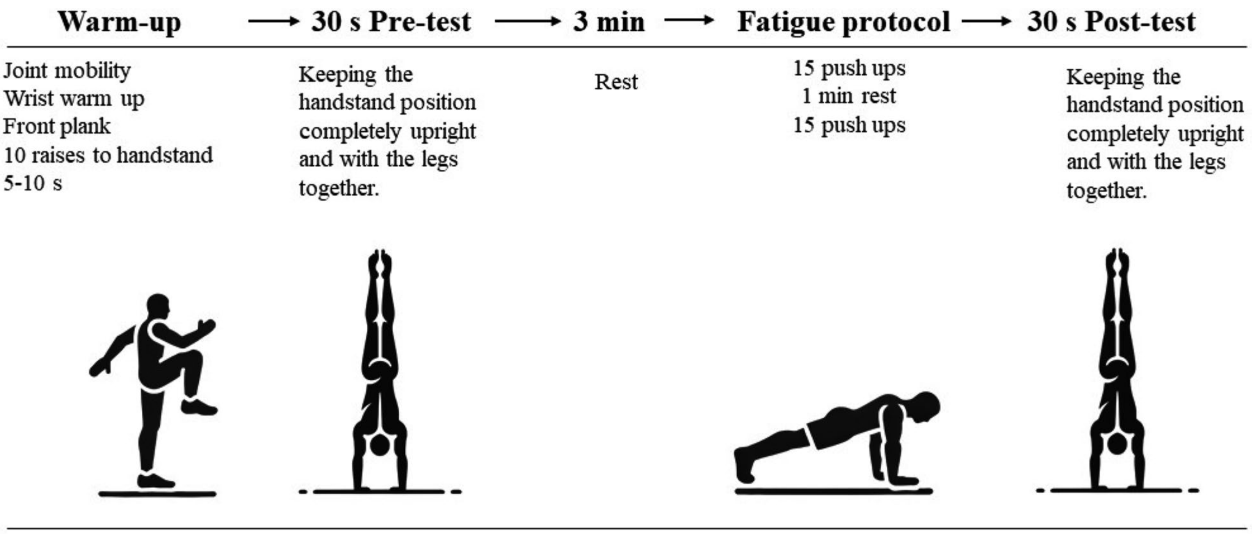

Fig. 2 Outline of the measurement procedure

assessed using bivariate variable error (BVE) and mean velocity magnitude (MVM) in the force plate. BVE was measured as the mean of the displacement to each participant's own midpoint, and MVM was measured as the average COP velocity [10]. Postural modifications on the floor were analyzed through COP area and force distributions measured by force plate. On the other hand, body behavior was measured through standard deviation (SD) from resultant acceleration collected by IMUs. The variables used to assess the complexity of force plate signals and acceleration from IMUs were FuEn, and DFA. FuEn indicates the degree of irregularity in the signal through to calculate the repeatability of vectors. On the other hand, DFA evaluates the presence of long-term correlations within time series [18]. FuEn was calculated using the formula (1) proposed by Chen et al. [14], with the following parameters m = 2, r = 0.2 and N = 2.

$$\mathrm{SampEn(m, r, N)} = -\ln\left(\frac{\mathrm{A}^{m}(\mathrm{r})}{B^{m}(r)}\right) \quad (1)$$

While the DFA following the algorithm (2) of Peng et al. [45], where windows from 4 to 50 data were calculated, which would be equivalent to one second.

$$\mathrm{F(n)} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\mathrm{y(k)} - y_n(\mathrm{k})]^{2}} \quad (2)$$

Statistical analysis

Data normality was evaluated with Kolmogorov–Smirnov test with the Lilliefors correction. A paired *t*-test was performed to study the possible significant influence of fatigue in handstand task. Results are expressed as means ± SD. Given the large number of variables analyzed, it was decided to apply the Bonferroni adjustment to determine significance; as this was an exploratory study, we adjusted the p-values by grouping them by device. Thus, the p-value was set at $p < 0.007$ to assume that the differences were significant. Effect size was calculated using standardized mean difference, Cohen's d, to provide a proportion of the overall variance that is attributable to the factor. Values of effect size ≥ 0.80 were considered strong, ≥ 0.50 moderate, and ≥ 0.20 were considered small [23]. All data were analyzed using the SPSS statistical package (v.22, SPSS Inc, Chicago, IL).

Table 1 Comparison between pre and post-fatigue protocol of linear measurements

Variable	Pre Mean ± SD	Post Mean ± SD	p	t	d
BVE	13.679 ± 2.818	14.854 ± 2.566	0.191	−1.378	−0.369
MVM	151.792 ± 35.641	154.271 ± 23.660	0.784	−0.280	−0.075
SD IMU FA	0.401 ± 0.196	0.416 ± 0.168	0.412	−0.847	−0.226
SD IMU AR	0.414 ± 0.181	0.402 ± 0.126	0.628	0.496	0.133
SD IMU C7	0.279 ± 0.121	0.294 ± 0.125	0.451	−0.778	−0.208
SD IMU L5	0.358 ± 0.146	0.412 ± 0.172	0.041	−2.146	−0.574
SD PLA X	7.428 ± 1.983	7.689 ± 1.534	0.339	−0.990	−0.265
SD PLA Y	4.246 ± 0.691	4.787 ± 0.823	0.007*	−3.160	−0.845
SD PLA Z	17.382 ± 3.359	18.327 ± 3.113	0.217	−1.300	−0.347
SD PLA AX	14.083 ± 2.811	14.808 ± 2.243	0.372	−0.930	−0.249
SD PLA AY	6.447 ± 1.660	7.756 ± 2.321	0.034	−2.370	−0.633
SD PLA MF	17.383 ± 3.360	18.325 ± 3.112	0.219	−1.290	−0.345
SD PLA MC	11.813 ± 3.724	13.400 ± 2.184	0.043	−2.130	−0.569

The values presented in Table 1 depict the comparison between pre- and post-fatigue protocol of linear measurements. Mean values and standard deviations (SD) are reported for each variable. The statistical analysis results include the p-value (p) and the outcomes of paired Student's t-test (t). The effect size measure (d) is utilized to assess the magnitude of the observed differences.

BVE: Bivariate variable error; MVM: Mean velocity magnitude; SD: Standard deviation; IMU: Inertial measurement unit; PLA: force platform; FA: Forearm; AR: Arm; C7: Seventh cervical vertebra; L5: Fifth lumbar vertebra; X: Antero-posterior axis of force platform; Y: Medium-lateral axis of force platform; Z: Vertical axis of force platform; AX: Antero-posterior axis of center of pressure; AY: Medio-lateral axis of center of pressure; MF: Modulus of force axis; MC: Modulus of center of pressure

*p < 0.007 indicates a significant difference.

Results

Before presenting the results of the analyses conducted on the complete 20-s signal, we conducted a comparative assessment to distinguish whether potential changes were induced by the fatigue protocol rather than the inherent handstand task. This comparison entailed examining the first and last 10 s of each measurement, both pre- and post-fatigue protocol, through t-tests. The primary aim was to confirm that any disparities between the pre- and post-fatigue periods were attributable to the fatigue protocol and not to accumulated fatigue during the task itself. Our analysis revealed no significant differences between the initial and final 10 s of the pre and post-fatigue measurements. This observation supports the conclusion that the previously noted differences in the pre-fatigue measure can be attributed to the fatigue protocol.

Table 1 presents the comparison from linear measurements between pre- and post-fatigue protocol. In terms of linear measurements, significant differences were observed only in the mediolateral axis (PLA Y) from the force plate, which showed an increase from pre to post-fatigue situations with a strong effect size. Conversely, other variables, such as the SD of L5 IMU, COP displacement in axis Y (AY), and modulus of COP (MC) from the force plate, while not reaching the new significance threshold, displayed strong trends. The effect sizes for these variables were moderate to strong, indicating a meaningful tendency towards significance.

Significant differences were found in DFA in the mediolateral (PLA Y) axis of the force platform, which exhibited a large effect size. For the other variables, such as DFA in the vertical axis (PLA Z) of the force platform, DFA in the MF, and FuEn in the sacral IMU, while the p-values did not meet the stricter significance threshold, these variables demonstrated moderate to strong trends supported by their large effect sizes. In the remaining nonlinear variables, no significant changes or potential trends were observed, with effect sizes ranging from small to medium.

Table 2 Comparison between pre and post-fatigue protocol of non-linear measurements

Variable	Pre Mean ± SD	Post Mean ± SD	p	t	d
DFA IMU FA	0.206 ± 0.140	0.200 ± 0.090	0.777	0.290	0.077
DFA IMU AR	0.326 ± 0.140	0.306 ± 0.098	0.588	0.556	0.148
DFA IMU C7	0.400 ± 0.067	0.421 ± 0.163	0.658	−0.454	−0.121
DFA IMU L5	0.184 ± 0.116	0.184 ± 0.075	0.988	0.015	0.004
DFA PLA X	0.907 ± 0.093	0.905 ± 0.077	0.922	0.100	0.027
DFA PLA Y	0.916 ± 0.173	1.056 ± 0.158	0.004*	−3.459	−0.924
DFA PLA Z	0.318 ± 0.126	0.486 ± 0.219	0.015	−2.809	−0.751
DFA PLA AX	1.252 ± 0.101	1.24 ± 0.108	0.531	0.644	0.172
DFA PLA AY	1.375 ± 0.152	1.376 ± 0.111	0.990	−0.013	−0.003
DFA PLA MF	0.318 ± 0.126	0.486 ± 0.219	0.015	−2.806	−0.750
DFA PLA MC	1.273 ± 0.098	1.238 ± 0.107	0.049	2.169	0.580
FuEn IMU FA	0.293 ± 0.161	0.305 ± 0.140	0.445	−0.788	−0.211
FuEn IMU AR	0.290 ± 0.125	0.286 ± 0.092	0.778	0.287	0.077
FuEn IMU C7	0.189 ± 0.081	0.199 ± 0.083	0.200	−1.350	−0.361
FuEn IMU L5	0.229 ± 0.104	0.267 ± 0.116	0.011	−2.958	−0.791
FuEn PLA X	1.401 ± 0.149	1.413 ± 0.142	0.741	−0.337	−0.090
FuEn PLA Y	1.445 ± 0.154	1.402 ± 0.202	0.366	0.937	0.250
FuEn PLA Z	2.014 ± 0.219	1.995 ± 0.247	0.742	0.336	0.090
FuEn PLA AX	0.557 ± 0.148	0.541 ± 0.123	0.629	0.495	0.132
FuEn PLA AY	0.543 ± 0.150	0.539 ± 0.111	0.861	0.179	0.048
FuEn PLA MF	2.014 ± 0.219	1.996 ± 0.247	0.744	0.334	0.089
FuEn PLA MC	0.620 ± 0.139	0.593 ± 0.124	0.491	0.708	0.189

The values presented in Table 2 depict the comparison between the pre- and post-fatigue protocol of non-linear measurements. Mean values and standard deviations (SD) are reported for each variable. The statistical analysis results include the p-value (p) and the outcomes of paired Student's t-tests (t). The effect size measure (d) is utilized to assess the magnitude of the observed differences.

DFA: Detrended fluctuation analysis; FuEn: Fuzzy entropy; IMU: Inertial measurement unit; PLA: force platform; FA: Forearm; AR: Arm; C7: Seventh cervical vertebra; L5: Fifth lumbar vertebra; X: Antero-posterior axis of force platform; Y: Medium-lateral axis of force platform; Z: Vertical axis of force platform; AX: Antero-posterior axis of center of pressure; AY: Medio-lateral axis of center of pressure; MF: Modulus of force axis; MC: Modulus of center of pressure

$^*p < 0.007$ indicates a significant difference

Discussion

In the present study, we investigated the influence of fatigue in the complexity of movement system variability during the performance of a handstand task. The non-linear analysis of the fluctuations of movement in the base of support is sensitive to the effects of fatigue in postural control as a complementary procedure to the traditional variables of analysis.

In the author's knowledge, this is the first study about the influence of fatigue during handstand task. Several constraints have been studied during handstand execution [3, 50]. Most of the studies found a change in behavior with different constraints application (e.g. type of surface, open-closed eyes or place vision), resulting in an increase in force production [3], COP displacement [17], or COP variance [25]. Our results are in partial agreement with these studies, finding a significant increase in the dispersion of forces applied in the base of support and COP way in the Y-axis (PLA Y) after the fatigue protocol. Similar results were found by Gautier et al. [25] during closed eyes or peripheral vision strategies as constraints during handstand. Furthermore, other variables such as the SD of L5 IMU, COP displacement in axis Y (AY), and MC from the force plate, while not reaching the new significance threshold, displayed strong trends. The effect sizes for these variables were moderate to high, indicating a meaningful tendency towards significance. IMU devices are new technologies recently applied in the gymnastic field [37], and they have been proven to be useful to provide feedback during gymnastic execution [5, 7]. Our results about the variability detected in L5 with IMUs can only be compared with studies where the hip has been studied with cinematography [22], showing a similar trend towards increased variability of the joint angle with a constraint related to head position.

Research on the application of non-linear analysis of movement using DFA or Entropy to analyze handstand performance is still scarce. Previously, only Pryhoda et al. [49] have applied non-linear tools to handstand description. Similar to our results, Pryhoda et al. found a reverse trend between complexity and SD when joint angles were analyzed during the handstand task. Isableu et al. [30] applied entropy to study COP regularity in gymnasts but during bipedal tasks. These authors exposed the utility of complexity analysis to show qualitative differences between gymnasts' and control participants' behavior, in a task where quantitative differences did not find. Our results are according to this idea because fatigue constraints led to some significant differences, especially in force plate variables. The loss of complexity observed through DFA increase after fatigue protocol according to previous studies. So, Pau et al. [44] found a decrease in COP complexity during upright balance after fatigue tasks in firefighters in accordance with the results from our study. Similar results were obtained by Lee et al. [36] after mental and physical fatigue using DFA as a variable to study COP complexity in quiet standing tasks. These authors found a decrease in DFA exponent in COP approached statistical significance after a 30-min mental fatigue-inducing task and calf raise task until exhaustion.

These results about a decrease in postural control complexity have been found in other tasks such as running [41] or isometric muscle contractions [46]. Results from those studies and ours would be according to the "loss of complexity hypothesis" which suggests a reduction in qualitative motor variability is produced by a reduction of degrees of freedom during a task [38]. Nevertheless, some authors have found opposite results showing an increase in entropy of COM accelerations during single-legged stance after fatigue induced by two Wingate tests [42]. These authors expose that fatigue can produce a diversion of attention during post-test situation, assuming the idea of Donker et al. [20] who defend an increase in postural complexity when attention is diverted during a dual task. However, in our study we did not observe the aforementioned reduction in complexity. Perhaps given the increased attention requirement due to the difficulty of the task, i.e. maintaining the handstand position compared to standing, it is possible that more attention is required, and thus the complexity tends to increase, as in the studies of Donker et al., even with the development of fatigue.

Nevertheless, the information about non-linear analysis from the accelerometer signal is different from that of the force plate. In this case, a trend towards a significant increase in FuEn has been observed after fatigue, reflecting a higher irregularity in this measure. According to previous studies, information from accelerometers and force plates could be different and complementary [35]. Non-linear analysis from a force plate informs about a freeze in degrees of freedom with fatigue (higher DFA), while entropy analysis from the L5 accelerometer shows a tendency towards higher irregularity as a result of fatigue. Accelerometer in L5 are more sensible to hip actions during handstand, a strategy not allowed to control balance in our protocol, but it is usual to observe this strategy when postural sway becomes too great [32] just as occurs in fatigue condition.

The use of accelerometers to measure motor variability has grown in the last few years. The possibility of providing alternative or complementary information to force plates in balance studies [1], and the low cost of these devices versus force plates [43] are reasons to find a high number of studies using accelerometry to assess balance tasks. In our study, data from accelerometers and force plates showed similar sensitivity to quantitative changes after fatigue induction. Thus, the IMU located at L5, close to the COM site, and the Y-axis or MC variables seem to be good indicators of fatigue influence, similar to the study by Adlerton et al. [1], who analysed COP displacement as a force plate variable. On the other hand, when the structure of motor variability is analyzed, results from force plate variables can be more sensitive to detect fatigue regarding data from IMUs, because only FuEn in IMU L5 showed a trend towards differentiation between pre and post fatigue constraints. In this way, our results indicate a more sensitive measure of the postural adjustments from the force plate versus accelerometry in opposition to the idea from McGregor et al. [41]. This could be explained because force production measured in the force plate results from participant behavior to maintain COM in the support base. In this way, complexity motor analysis reflects as fatigue has an important influence on the participant's ability to show successful behavior.

Conclusions

This study aimed to investigate the influence of fatigue in handstand tasks through force plate and accelerometers and under linear and non-linear analysis. Force plate and one of the accelerometers (ubicated in L5) show a tendency to detect changes in the amount of variability after a fatigue condition. Furthermore, non-linear analysis based on DFA is only sensitive from force plate signal and not from the accelerometer. In the accelerometer signal a trend towards an increase in irregularity can be observed as a possible change of hip control during handstand as a result of fatigue and the increase in COP way. In this way, the accelerometer can be implemented to assess handstand tasks during fatigue protocols through linear analysis (quantitative variability). On the other hand, if coaches or researchers want to detect qualitative changes in variability, a force plate is the recommended device.

It is important to note that this is an exploratory study. More research is needed to fully understand which variables are most useful in detecting fatigue-related changes in handstand tasks. Future studies should aim to validate these findings with larger sample sizes and in different contexts to determine the generalizability and applicability of these measures.

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Author contributions

Conceptualization, R.S.; methodology, R.S, F.G. and F.M.; software, F.G-A. and F.M.; formal analysis, F.G-A.; investigation, R.S. and; resources, R.S. and C.C.; data curation, F.G.; writing—original draft preparation, R.S and F.G-A.; writing—review and editing, C.C. and F.M.; supervision, R.S. and F.M. RS: Conceptualization (equal), Supervision, Writing/Original Draft (equal), Methodology (equal). F G-A: Data Curation (equal), Investigation (equal), Formal Analysis (lead), Writing/Original Draft (equal). CC: Investigation (equal), Methodology (equal), Writing/Review & Editing (equal). FM: Conceptualization (equal), Supervision, Writing/Review & Editing (equal), Methodology (equal).

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request. Similarly, the codes used to perform the variability analyses are available upon request to the corresponding author. The data is available to any reader upon request to the corresponding author.

Declarations

Ethics approval and consent to participate

The study was conducted in accordance with the Declarationof Helsinki and approved by the Office of Responsible Research (OIR). The University's ethics committee approved the research ethics statement under register 2019.417.E.OIR; 2020.34.E.OIR and reference DCD.RSS.02.19. Each subject provided written informed consent, which was approved by the ethics committee of the University (PID2019-109632RB-100) and which adhered to the Declaration of Helsinki.

Consent for publications

All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

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