Acta of Bioengineering and Biomechanics
Vol. 25, No. 2, 2023

Original paper
DOI: 10.37190/ABB-02293-2023-02

General muscle fatigue changed joint regulations in static and dynamic balance

MASUMEH BABAYI[1], SAYED MOHSEN MORTAZAVI NAJAFABADI[2],
MOHAMMED N. ASHTIANI[3]*, DARIUSZ GRZELCZYK[2]

[1] Faculty of Biomedical Engineering, Sahand University of Technology, Tabriz, Iran.
[2] Department of Automation, Biomechanics and Mechatronics, Lodz University of Technology, Łódź, Poland.
[3] Department of Physical Therapy, Faculty of Medical Sciences, Tarbiat Modares University, Tehran, Iran.

This study was aimed at investigating the joint regulations and body sway after general muscle fatigue during tasks that involve both static and dynamic balance. This cross-sectional study used motion analysis to ascertain the kinematic changes in twelve healthy young individuals before and after running-induced fatigue. Six linear and nonlinear stability metrics were calculated to assess the whole body and joint-related variations. Significant instabilities were observed in the hip and specifically in the knee mechanisms and the whole body during the static condition. Velocity path length and approximate entropy for knee ($p = 0.019$, $p = 0.027$) and hip ($p = 0.016$, $p = 0.042$) were significantly greater after fatigue. These parameters for the whole body center of mass were also higher after fatigue ($p = 0.013$, $p = 0.013$). General muscle fatigue did not significantly affect the ankle during static and dynamic standing ($p > 0.05$). Dynamic standing did not reveal the effects of fatigue either on local joint regulations or on the whole body except for the nonlinear metrics of the proximal joints. The knee and hip were adversely affected by fatigue while the ankle strove to compensate for the fatigue-induced instability.

Key words: *postural control, running-induced fatigue, standing strategies, balance*

1. Introduction

Postural control plays a vital role in both daily and sports activities [37]. Postural stability refers to the ability to regulate the center of mass (CoM) within the base of support to avoid falling in relation to the supporting base [25], which is not so simple even for healthy people when faced with internal or external perturbations [31]. The central nervous system needs to combine sensory inputs from the visual, vestibular and somatosensory systems to uphold postural stability [17]. The literature has made a distinction between static and dynamic postural balance control. Static balance control refers to the ability to maintain balance in a stable environment, such as standing still on a solid surface [30]. On the other hand, dynamic balance control refers to the ability of human neuromuscular system to adjust the body segments in response to sudden changes in environmental conditions. These changes may include physical perturbations like movement of the base of support, sensory perturbations like elimination of visual or somatosensory feedback or inducing any defect in adequate and prompt muscle activation [31]. The latter may be induced by some neuromuscular disorders or by fatigue [26].

Fatigue is defined as a reduction in the ability of muscles to produce force, which is crucial in postural control [24]. Apart from the diminished efficiency of the muscular system, muscle fatigue can also impair the transmission and/or integration of sensory proprioceptive and environmental information into the central nervous system [21]. Also, fatigue can disrupt the transmission of neural signals to the muscles [33]

---

* Corresponding author: Mohammed N. Ashtiani, Faculty of Medical Sciences, Tarbiat Modares University, Tehran, Iran. Phone: +98 21 8288 5054, e-mail: mnashtiani@modares.ac.ir

Received: August 3rd, 2023
Accepted for publication: October 11th, 2023

or adversely affect neural excitations [38], leading to postural instability [35]. There are a significant number of studies exploring the relationship between muscle fatigue and interference with postural stability [23]. These studies have demonstrated that fatigue causes an increase in postural sway and reduces lower extremity reaching or weight-shifting performance (i.e., dynamic balance).

Muscular fatigue may be induced locally or generally. Local muscle fatigue refers to a reduction in force generation ability in a specific muscle group that contributes to standing. Researchers have investigated the effects of local fatigue on balance, often inducing fatigue through exercises or isokinetic tasks and then examining its effect on balance under different conditions such as elimination of vision, and uni-pedal stance [20], [24]. The literature, however, found no consensus on the greater effects of fatigue in local muscle groups on balance [21], [13].

In contrast, general muscular exercises such as running, cycling or rowing involve multiple joints and result in spatial movement of the entire body during standing [10], [32]. General fatigue, regardless of the cause, can impair the central nervous system's ability to regulate exercise and heighten the chances of muscle and bone injuries [27]. To the authors' knowledge, there are limited studies that have examined the impact of general fatiguing exercises on postural control. Zech et al. Investigated the effect of general muscle fatigue on static and dynamic balance in a series of athletes and found that fatigue has an impact on static postural control, but dynamic balance control in healthy athletes remains largely unaffected [40]. Fatigue, on the other hand, may affect afferent nerves via decreased sensory perception, impaired reflexes, increased sensitivity, slowed nerve conduction, increased risk of overuse injuries, and, of more importance, altered muscle control by reducing proprioceptive acuity [9], [36].

Maintenance of the balance either in static or in dynamic modes of postural control needs a prompt joint work between the neural feedback and muscle contractions not only in a certain joint but also in all lower limb muscles and even in the core region. Fatigue of the wide range of muscles by general protocols may have a different impact on the body balance comparing specific local muscle fatigue conditions. Therefore, the goal of the present study was to examine how general muscle fatigue affects the regulation of lower limb joints and overall stability in both static and dynamic support surfaces. It was hypothesized that general muscular fatigue reduces postural stability by altering typical joint mechanisms that guarantee the maintenance of balance.

2. Materials and methods

Twelve (six males and six females) healthy adults (aged 26.5 ± 4.1 years, weight of 69.1 ± 5.7 kg, and height of 169 ± 6 cm) volunteered to participate in this study. They were recruited from the university and its dormitories by paper and electronic flyers. The inclusion criteria were age between 18 and 40 years, no history of nervous, cardiac, muscular or joint-related disorders, recent injury or surgery and diabetes. The exclusion criteria were consumption of alcohol or smoking, professional or college athletic training and having insomnia the night before the test. The participants were all students and university staffs. The protocol of the test was prepared based on the Declaration of Helsinki, which was approved by the Committee of Ethics in medical research of Tarbiat Modares University. The participants received both verbal and written information and signed the consent form.

The participants were asked to stand in two static (ST) and dynamic (DY) support surface conditions. In the ST condition, the participants were asked to stand quietly on a firm support. The DY condition, however, used an unstable support which has been formed by a 40 cm × 45 cm Plexiglas plate that is fixed on a horizontal semi-ellipse (minor axis radius = 10 cm) and supported by two similar springs ($k = 3.4$ kN/m). The participants, again, were asked to stand barefoot with legs apart equal to the shoulders width, cross their arms in front of their chest, look forward and keep their balance to prevent falling. These balance tests were performed in two pre- and post-fatigue conditions. Each test was repeated in three 30-second trials. The reasons behind the use of this type of dynamic conditions referred to the fact that standing on an unsteady surface causes increased muscular activation and movement. Such surfaces necessitate a substantially larger increase in lower-leg muscular activation when standing than a firm floor and it is a difficult physical task to do even for the healthy young individuals. The degree of support sway in such perturbations is mutually dependent on the ability of the individuals which mandates use of more muscles and standing strategies.

General muscular fatigue was induced for each participant by an aerobic physical exercise. The participants were asked to run on a treadmill for 21 minutes with a speed ascending from 2.7 to 9.6 km/h according to the Bruce protocol for fatigue (Fig. 1). This protocol had been compared to other similar ones in terms of different fatigue indices like the rate of oxygen intake, maximum heart rate, blood pressure, etc. It

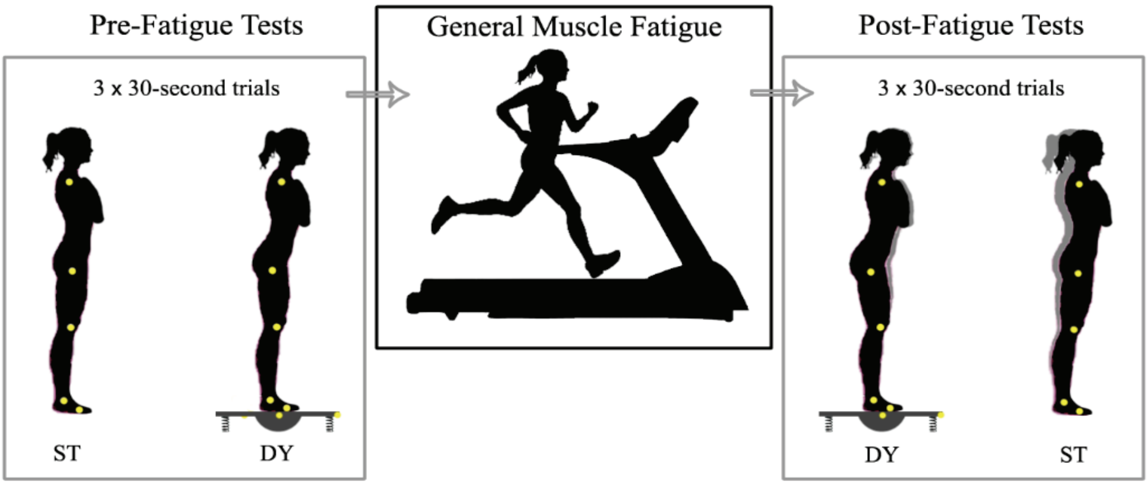


Fig. 1. Graphical flowchart of the test. Lighted points on the model illustrate the markers on 5th metatarsal, lateral malleolus, lateral femoral condyle, greater trochanter and acromion process. ST (static), DY (dynamic) support surface

was found that there is no significant difference between the Bruce protocol of fatigue and the others [34]. The heart rate of the participants was visually monitored to be greater than 60% of their maximum rate for the last 10 minutes of the running to assure that the general muscle fatigue is fulfilled [28]. The maximum rate of the participants was measured a week earlier than the test day.

Joint kinematics were registered using motion capture. A high-speed camera (Casio® EX-ZR20, Tokyo, Japan) recorded the motions of the markers at 120 frames/s sampling frequency. Five active LED markers were attached to the bone landmarks of the joints (fifth metatarsal, lateral malleolus, lateral femoral condyle, greater trochanter and acromion process) to determine the joint angles during postural control. Since the body uses definite joint strategies in maintaining stability, these markers can properly ascertain the kinematic changes in postural adjustment [1], [18]. The captured videos were analyzed by a customized planar image processing code. The extra details about the motion analysis system are illustrated in Fig. 1. Although the reliability of planar motion analysis was previously assessed [11], intra-class correlation coefficients were calculated to show excellent to good reliability of the present data acquisition.

Having extracted the joint angles, anterior-posterior displacements of the CoM were calculated by weighted averaging between the body segments for each participant. A wide range of metrics including linear and nonlinear metrics was calculated based on the CoM excursions and the joint variations in the lower extremities in MATLAB (MathWorks Inc., MA, USA). These metrics were root mean square (RMS), path length (PL), velocity path length (VPL), variability (Var), phase plane portrait (PPP) and approximate entropy (ApEn). More information about the definitions of these parameters is developed in papers [2], [7], or Table A1 in the appendix. The body's CoM was calculated based on Eq. (1):

$$CoM = \frac{\sum_{1}^{3} m_i x_i}{\sum_{1}^{3} m_i}, \tag{1}$$

where m and x are segmental mass and center of mass for $i = 1$, 2 and 3 representing shank, thigh, and trunk segments. These values were adopted based on the anthropometric tables [8].

Paired-sampled t-test was used to compare balance outcomes before and after fatigue in static and dynamic standing conditions if the distribution of data was normal based on Shapiro–Wilk test of normality. The significance level was set at 0.05 for all statistical analyses.

3. Results

In Table 1, calculated metrics for all test cases based on the ankle, knee and hip rotations, and the CoM anterior-posterior excursion are presented. Comparison of the CoM metrics as a global measure of stability with the local multi-joint coordination unveils the overall effects of fatigue and support and the possible compensatory mechanisms of the neuro-musculoskeletal system.

Table 1. Statistical details (mean ± SD) for six metrics of stability in the lower limb joints and CoM before and after the fatigue in two static and dynamic standing conditions

Parameter	Before				After			
	ankle	knee	hip	CoM	ankle	knee	hip	CoM
Static								
RMS	2.9 ± 3.4	8.8 ± 9.7	2.8 ± 3.5	6.2 ± 5.5	2.0 ± 2.4	9.1 ± 10.3	3.3 ± 4.1	4.7 ± 2.8
Var	0.5 ± 0.4	0.5 ± 0.4	0.4 ± 0.4	3.1 ± 2.2	0.5 ± 0.3	0.6 ± 0.4	0.5 ± 0.3	3.1 ± 1.7
PL	0.8 ± 1.3	0.4 ± 0.3	0.3 ± 0.2	0.1 ± 0.1	0.7 ± 0.7	0.7 ± 0.4	0.5 ± 0.3	0.2 ± 0.1
VPL	0.4 ± 0.6	0.2 ± 0.1	0.2 ± 0.1	.04 ± .04	0.4 ± 0.5	0.2 ± 0.2	0.2 ± 0.1	0.1 ± 0.1
PPP	7.5 ± 9.0	4.8 ± 2.6	4.3 ± 1.5	1.2 ± 0.9	8.4 ± 4.9	6.7 ± 2.8	5.7 ± 1.7	1.8 ± 0.9
ApEn	0.2 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	0.3 ± 0.1
Dynamic								
RMS	3.4 ± 4.1	8.2 ± 9.6	3.4 ± 3.7	7.0 ± 3.5	3.0 ± 3.2	7.6 ± 8.8	3.1 ± 3.1	7.5 ± 2.7
Var	1.0 ± 0.9	1.1 ± 1.0	1.0 ± 1.2	4.3 ± 2.8	1.2 ± 1.2	0.9 ± 0.7	0.9 ± 0.6	4.7 ± 2.5
PL	1.4 ± 1.3	0.9 ± 0.5	0.6 ± 0.3	0.2 ± 0.2	1.9 ± 1.4	1.0 ± 0.4	0.7 ± 0.3	0.3 ± 0.1
VPL	0.4 ± 0.3	0.3 ± 0.2	0.2 ± 0.1	0.1 ± 0.1	0.4 ± 0.3	0.3 ± 0.2	0.3 ± 0.1	0.1 ± 0.1
PPP	12.0 ± 9.2	8.3 ± 3.4	7.1 ± 2.6	2.2 ± 1.2	15.6 ± 8.5	8.8 ± 3.0	7.0 ± 1.9	2.4 ± 1.1
ApEn	0.3 ± 0.2	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.2	0.4 ± 0.1	0.4 ± 0.1	0.3 ± 0.1

Static standing condition

The ankle mechanism in quiet standing cases was not affected by general muscle fatigue ($p > 0.05$). Although not significant, the ApEn mean values for the ankle rotations during quiet standing were more different ($p = 0.069$). The same outcomes were achieved in the dynamic cases of standing, in which none of the postural metrics showed significant difference before and after imposing general muscle fatigue ($p > 0.184$). Statistical details are presented in Table 2.

Table 2. Statistical comparison between postural metrics in static and dynamic standing conditions before and after general muscle fatigue in terms of p-values. The bold-faced values denote significant effects ($p < 0.05$)

Parameter	Fatigue effect p-value			
	ankle	knee	hip	CoM
Static				
RMS	0.240	0.454	0.152	0.303
Var	0.876	**0.037**	0.205	0.868
PL	0.791	**0.016**	0.051	**0.013**
VPL	0.555	**0.019**	**0.016**	**0.013**
PPP	0.898	**0.027**	0.083	**0.012**
ApEn	0.069	**0.027**	**0.042**	**0.013**
Dynamic				
RMS	0.535	0.631	0.598	0.339
Var	0.210	0.404	0.405	0.094
PL	0.308	0.318	0.277	0.322
VPL	0.810	0.156	0.249	0.290
PPP	0.184	0.359	0.845	0.197
ApEn	0.222	**0.044**	**0.006**	0.403

The knee mechanism, however, showed a significant increase in the postural metrics of stability while participants stood quietly. Only the RMS values before and after the fatigue remained unchanged ($p = 0.454$). In contrast, variability ($p = 0.037$, $t = -2.37$, $d = 0.69$), path length ($p = 0.016$, $t = -2.85$, $d = 0.82$), velocity path length ($p = 0.019$, $t = -2.75$, $d = 0.79$), phase plane portrait ($p = 0.027$, $t = -2.56$, $d = 0.74$), and approximate entropy ($p = 0.027$, $t = -2.56$, $d = 0.74$) were all increased after fatigue. In the dynamic condition, on the other hand, merely approximate entropy showed a significant increase ($p = 0.044$, $t = -2.27$, $d = 0.65$). Other postural metrics were unchanged after fatigue ($p > 0.156$).

Local stability metrics related to hip joint rotations showed increases in velocity path length ($p = 0.016$, $t = -2.83$, $d = 0.81$) and approximate entropy ($p = 0.042$, $t = -2.29$, $d = 0.66$). Other metrics like variability, path length, RMS and PPP showed same results before and after general muscle fatigue ($p > 0.051$). Dynamic standing on the unstable platform showed insignificant changes in postural metrics ($p > 0.150$) unless approximate entropy ($p = 0.006$, $t = -3.43$, $d = 0.99$).

The CoM of the participants' body in the static standing condition showed significant increases in path length ($p = 0.013$, $t = -2.97$, $d = 0.85$), velocity path length ($p = 0.013$, $t = -2.97$, $d = 0.85$), PPP ($p = 0.012$, $t = -2.99$, $d = 0.86$), and approximate entropy ($p = 0.012$, $t = -2.99$, $d = 0.86$). Variability and RMS of the CoM remained unchanged ($p > 0.303$). Nevertheless, all postural metrics in the dynamic condition of standing showed insignificant changes ($p > .094$).

4. Discussion

Postural control requires joint regulations to confine the vertical projection of the center of mass within the base of support based on the appropriate muscular recruitment. Depending on postural, environmental or sensory conditions, the central nervous system decides to adjust posture in response to possible perturbations [2], [6], [16]. Postural adjustment, which involves a set of changes in body joint positions commanded by the CNS to reduce CoM movement, may vary depending on the conditions. Standing in upright, quiet postures may require reducing joint rotations to limit CoM excursions by inducing more muscle co-activation. In contrast, standing in a perturbed case, such as standing on a narrowed or unstable support, may require more regulations of the joints in order to align the horizontal position of the CoM with the point of rotation [19]. Although the overall variations of the CoM in these cases may be inherently greater than in quiet or unperturbed conditions, increasing joint stiffness may not be the right or, at least, the only strategy at play since the body transfers the support movement as a rigid body motion to the center of mass. This may cause a sudden and large movement of the CoM out of the base of support, leading to instability or a fall. Therefore, the decisions of the CNS are closely dependent on the tasks and situations. The rationale behind selecting two different support surface conditions in the present study was to investigate the possible strategies for enhancing body stiffness during static tasks and adapting postures during dynamic activities.

Fatigue can affect postural control through disruption of proprioception and muscle weakness [22], [33]. It is important to note that fatigue is not task-dependent, as per its definition [4]; however, its effects may vary among the conditions. Since the fatigue in this study is generally induced by an aerobic exercise, the CNS is not forced to adjust the posture to compensate for local fatigue consequences. Therefore, the regulations of the joints after general fatiguing may be more crucial to identify the multi-joint coordination of the posture after fatigue.

Ankle Joint was surprisingly not affected after the fatigue. Neither the static nor the dynamic standing condition showed significant changes in all six metrics of stability. The average ApEn values for ankle movements during quiet standing suggested a tendency for increased variability, but this distinction did not reach statistical significance. This finding is not consistent with the theory proposed by some researchers who found that inducing fatigue in ankle muscles led to an increase in postural sway and can considerably impair the lower joints' proprioception [3] leading to postural instability [14]. The primary finding of this study pertains to the lack of significant difference in the response of the CoM to fatigue in the dynamic condition. It disclosed that the young participants could overbear the neural and muscular effects of the fatigue. However, it did not mean that the body stood firmly. The prosperous limitation of the CoM movements as an index of stability was fulfilled by considerable adjustment of the posture. The linear metrics of the stability remained unchanged during dynamic standing but the nonlinear one, i.e., approximate entropy was significantly increased in the knee and hip mechanisms. It meant less regularity in joint rotations. Regarding the same linear metrics, it might disclose that maintaining the balance in dynamic conditions is hardly provided.

In this research, we discovered that the knee mechanism had an impact on various metrics related to static balance, excluding RMS. Following fatigue in the lower extremities, a significant contrast was observed between pre-fatigue and post-fatigue states in the knee and hip mechanisms. There were several studies that compared proximal muscle fatigue (like hip or lumbar muscles) with distal ones (like ankle tibialis anterior and calf muscles) indicating that, during the static balance tests, the effects of proximal muscles are greater and the joint regulations are closely dependent on the task [5]. Li et al. examined the effects of fatigue in badminton athletes. They observed that fatigue was more pronounced in the muscles surrounding the knee joint compared to other joints. They speculated that during fatigue, the nerves activated additional muscle units to sustain body balance [23]. In another study, Negahban and her colleagues conducted a study to explore the impact of fatigue on the dynamic balance of individuals suffering from patellofemoral pain syndrome (PPS). Interestingly, their findings align closely with our own research [29]. Additionally, Ghram et al. demonstrated in another study that knee muscle fatigue has a more pronounced effect on postural control compared to ankle fatigue [12]. Moreover, Vuillerme et al. suggested that after fatigue sets in, the central nervous system's reliance on the ankle may decrease [39]. The similarity in results between the aforementioned studies and our own can be attributed to the understanding that the proximal muscles of the lower extremity play a crucial role in maintaining balance, especially in challenging static conditions [15], [35]. Results of the present study, although in the kinematic framework, were in coincidence with them.

This study faced some limitations. First, the participants were only entered from the university people (students and staffs) that their sedentary life styles should be considered during interpretation of the results. Second, the participants' static or dynamic balance were not assessed before the test, which it had better to be considered in inclusion criteria. The examiners supposed that the young healthy adult have no balance disorder.

5. Conclusions

The present study showed that many features measuring the local joint stabilities or the whole body stability consistently reveal the vulnerability of the knee and hip to general muscle fatigue regarding balance maintenance in static standing. The dynamic standing needed more joint efforts so that the effects of fatigue were concealed. However, the nonlinear approximate entropy showed knee and hip strives to keep the balance.

Acknowledgements

This work has been completed while the second author was the Doctoral Candidate in the Interdisciplinary Doctoral School at the Lodz University of Technology, Poland.

Conflict of interest

The authors declare no conflict of interest.

References

[1] ASHTIANI M.N., AZGHANI M.R., *Effects of Visual and Cognitive Interference on Joint Contributions in Perturbed Standing: A Temporal and Spectral Analysis*, Australasian Physical and Engineering Sciences in Medicine, 2018, 41 (1), https://doi.org/10.1007/s13246-017-0606-7

[2] ASHTIANI M., AZGHANI M., *Open- and Closed-Loop Responses of Joint Mechanisms in Perturbed Stance under Visual and Cognitive Interference*, Biomedical Signal Processing and Control, 2018, 42, https://doi.org/10.1016/j.bspc.2018.01.005

[3] BARBIERI F.A., PENEDO T., SIMIELI L., BARBIERI R.A., ZAGATTO A.M., VAN DIËEN J.H., PIJNAPPELS M.A.G.M., RODRIGUES S.T., POLASTRI P.F., *Effects of Ankle Muscle Fatigue and Visual Behavior on Postural Sway in Young Adults*, Frontiers in Physiology, 2019, 10 (Jun.). https://doi.org/10.3389/fphys.2019.00643

[4] BIGLAND-RITCHIE B., WOODS J.J., *Changes in Muscle Contractile Properties and Neural Control during Human Muscular Fatigue*, Muscle and Nerve, 1984, 7 (9), 691–699, https://doi.org/10.1002/mus.880070902

[5] BISSON E.J., MCEWEN D., LAJOIE Y., BILODEAU M., *Effects of Ankle and Hip Muscle Fatigue on Postural Sway and Attentional Demands during Unipedal Stance*, Gait and Posture, 2011, 33 (1), https://doi.org/10.1016/j.gaitpost.2010.10.001

[6] CHIBA RYOSUKE, KAORU TAKAKUSAKI, JUN OTA, ARITO YOZU, NOBUHIKO HAGA, *Human Upright Posture Control Models Based on Multisensory Inputs; in Fast and Slow Dynamics*, Neuroscience Research, 2016, https://doi.org/10.1016/j.neures.2015.12.002

[7] COLLINS J.J., DE LUCA C.J., *Open-Loop and Closed-Loop Control of Posture: A Random-Walk Analysis of Center-of-Pressure Trajectories*, Experimental Brain Research, 1993, 95 (2), https://doi.org/10.1007/BF00229788

[8] DRILLIS R., CONTINI R., *Segment Length Expressed as Ratio of Body Height*, New York: Office of Vocational Rehabilitation, 1966, No. 1166.

[9] EDWARDS W.B., *Modeling Overuse Injuries in Sport as a Mechanical Fatigue Phenomenon*, Exercise and Sport Sciences Reviews, 2018, 46 (4), https://doi.org/10.1249/JES.0000000000000163

[10] ENOKA R.M., DUCHATEAU J., *Muscle Fatigue: What, Why and How It Influences Muscle Function*, Journal of Physiology, 2008, https://doi.org/10.1113/jphysiol.2007.139477

[11] FONDA B., SARABON N., LI F.X., *Validity and Reliability of Different Kinematics Methods Used for Bike Fitting*, Journal of Sports Sciences, 2014, 32 (10), https://doi.org/10.1080/02640414.2013.868919

[12] GHRAM A., JERIBI S., YAHIA A., ELLEUCH M.H., *Effect of General and Local Fatigue on Postural Control during Unipedal Quiet Standing of Athlete*, Annals of Physical and Rehabilitation Medicine, 2014, 57, https://doi.org/10.1016/j.rehab.2014.03.697

[13] GHRAM A., YOUNG J.D., SOORI R., BEHM D.G., *Unilateral Knee and Ankle Joint Fatigue Induce Similar Impairment to Bipedal Balance in Judo Athletes*, Journal of Human Kinetics, 2019, 66 (1), https://doi.org/10.2478/hukin-2018-0063

[14] GIMMON Y., RIEMER R., ODDSSON L., MELZER I., *The Effect of Plantar Flexor Muscle Fatigue on Postural Control*, Journal of Electromyography and Kinesiology, 2011, 21 (6), https://doi.org/10.1016/j.jelekin.2011.08.005

[15] GRIBBLE P.A., HERTEL J., *Effect of Lower-Extremity Muscle Fatigue on Postural Control*, Archives of Physical Medicine and Rehabilitation, 2004, 85 (4), https://doi.org/10.1016/j.apmr.2003.06.031

[16] HETTICH G., ASSLÄNDER L., GOLLHOFER A., MERGNER T., *Human Hip-Ankle Coordination Emerging from Multisensory Feedback Control*, Human Movement Science, 2014, 37, https://doi.org/10.1016/j.humov.2014.07.004

[17] HORAK F.B., *Postural Orientation and Equilibrium: What Do We Need to Know about Neural Control of Balance to Prevent Falls?*, In Age and Ageing, 2006, Vol. 35. https://doi.org/10.1093/ageing/afl077

[18] HORAK F.B., KLUZIK J., HLAVACKA F., *Velocity Dependence of Vestibular Information for Postural Control on Tilting Surfaces*, Journal of Neurophysiology, 2016, 116 (3), https://doi.org/10.1152/jn.00057.2016

[19] IVANENKO Y.P., LEVIK Y.S., TALIS V.L., GURFINKEL V.S., *Human Equilibrium on Unstable Support: The Importance of Feet-Support Interaction*, Neuroscience Letters, 1997, 235 (3), https://doi.org/10.1016/S0304-3940(97)00721-0

[20] JAHJAH A., SEIDENSPINNER D., SCHÜTTLER K., KLASAN A., HEYSE T.J., MALCHERCZYK D., BILAL FAROUK EL-ZAYAT,

The Effect of Ankle Tape on Joint Position Sense after Local Muscle Fatigue: A Randomized Controlled Trial, BMC Musculoskeletal Disorders, 2018, 19 (1), https://doi.org/10.1186/s12891-017-1909-2

[21] Lepers R., Bigard A.X., Diard J.P., Gouteyron J.F., Guezennec C.Y., *Posture Control after Prolonged Exercise*, European Journal of Applied Physiology and Occupational Physiology, 1997, 76 (1), https://doi.org/10.1007/s004210050212

[22] Liu Y., Song Q., Zhou Z., Chen Y., Wang J., Tian X., Sun W., *Effects of Fatigue on Balance and Ankle Proprioception during Drop Landing among Individuals with and without Chronic Ankle Instability*, Journal of Biomechanics, 2023, 146, https://doi.org/10.1016/j.jbiomech.2022.111431

[23] Liu Z., Yang C., Yu J., Zhao X., Wu J., Zhang Y., Li J., Gu Y., *The Effect of Muscles Fatigue on the Knee's Kinetics and Kinematics Characteristics*, Sustainability (Switzerland), 2023, 15 (4), https://doi.org/10.3390/su15043029

[24] Lyu H., Fan Y. Hao Z., Wang J., *Effect of Local and General Fatiguing Exercises on Disturbed and Static Postural Control*, Journal of Electromyography and Kinesiology, 2021, 56, https://doi.org/10.1016/j.jelekin.2020.102487

[25] Maki B.E., McIlroy W.E., *Postural Control in the Older Adult*, Clinics in Geriatric Medicine, 1996, 12 (4), 635–658, https://doi.org/10.1016/S0749-0690(18)30193-9

[26] Miles M.P., Ives J.C., Vincent K.R., *Neuromuscular Control Following Maximal Eccentric Exercise*, European Journal of Applied Physiology and Occupational Physiology, 1976, 76 (4), https://doi.org/10.1007/s004210050263

[27] Miura K., Ishibashi Y., Tsuda E., Okamura Y., Otsuka H., Toh S. *The Effect of Local and General Fatigue on Knee Proprioception*, Arthroscopy – Journal of Arthroscopic and Related Surgery, 1976, 20 (4), https://doi.org/10.1016/j.arthro.2004.01.007

[28] Nardone A.,, Tarantola J., Giordano A., Schieppati M., *Fatigue Effects on Body Balance*, Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control, 1976, 105 (4), 309–320, https://doi.org/10.1016/S0924-980X(97)00040-4

[29] Negahban H., Etemadi M., Naghibi S., Emrani A., Mohammad Jafar Shaterzadeh Yazdi, Reza Salehi, Aida Moradi Bousari, *The Effects of Muscle Fatigue on Dynamic Standing Balance in People with and without Patellofemoral Pain Syndrome*, Gait and Posture, 1976, 37 (3), https://doi.org/10.1016/j.gaitpost.2012.07.025

[30] Nelson J.K., Johnson B.L., *Effects of Local and General Fatigue on Static Balance*, Perceptual and Motor Skills, 1976, 37 (2), https://doi.org/10.2466/pms.1973.37.2.615.

[31] Paillard T., *Effects of General and Local Fatigue on Postural Control: A Review*, Neuroscience and Biobehavioral Reviews, 1976, https://doi.org/10.1016/j.neubiorev.2011.05.009

[32] Paillard T., *Relationship between Sport Expertise and Postural Skills*, Frontiers in Psychology, 1976, https://doi.org/10.3389/fpsyg.2019.01428

[33] Pedersen J., Ljubisavljevic M., Bergenheim M., Johansson H., *Alterations in Information Transmission in Ensembles of Primary Muscle Spindle Afferents after Muscle Fatigue in Heteronymous Muscle*, Neuroscience, 1976, 84 (3), https://doi.org/10.1016/S0306-4522(97)00403-X

[34] Pollock M.L., Bohannon R.L., Cooper K.H., Ayres J.J., Ward A., White S.R., Linnerud A.C., *A Comparative Analysis of Four Protocols for Maximal Treadmill Stress Testing*, American Heart Journal, 1976, 92 (1), https://doi.org/10.1016/S0002-8703(76)80401-2

[35] Salavati M., Moghadam M., Ebrahimi I., Arab A.M., *Changes in Postural Stability with Fatigue of Lower Extremity Frontal and Sagittal Plane Movers*, Gait and Posture, 2007, 26 (2), https://doi.org/10.1016/j.gaitpost.2006.09.001

[36] Sánchez-Zuriaga D., Adams M.A., Dolan P., *Is Activation of the Back Muscles Impaired by Creep or Muscle Fatigue?*, Spine, 2010, 35 (5), https://doi.org/10.1097/BRS.0b013e3181b967ea

[37] Santos R., Dos J.A., Silva Pirôpo Uanderson, da Silva Passos R., Lomanto Couto D., dos Santos A.M., Barbosa Argolo A.M., Helder Brito Andrade, Casotti C.A., Pereira R., *Influence of Trunk Extensor Muscles Fatigue on the Postural Control and Sensorimotor Integration*, Journal of Functional Morphology and Kinesiology, 2017, 2 (1), https://doi.org/10.3390/jfmk2010005

[38] Taylor J.L., Butler J.E., Gandevia S.C., *Changes in Muscle Afferents, Motoneurons and Motor Drive during Muscle Fatigue*, European Journal of Applied Physiology, 2000, 83 (2–3), 106–115, https://doi.org/10.1007/s004210000269

[39] Vuillerme N.,, Danion F., Forestier N., Nougier V., *Postural Sway under Muscle Vibration and Muscle Fatigue in Humans*, Neuroscience Letters, 2002, 333 (2), https://doi.org/10.1016/S0304-3940(02)00999-0

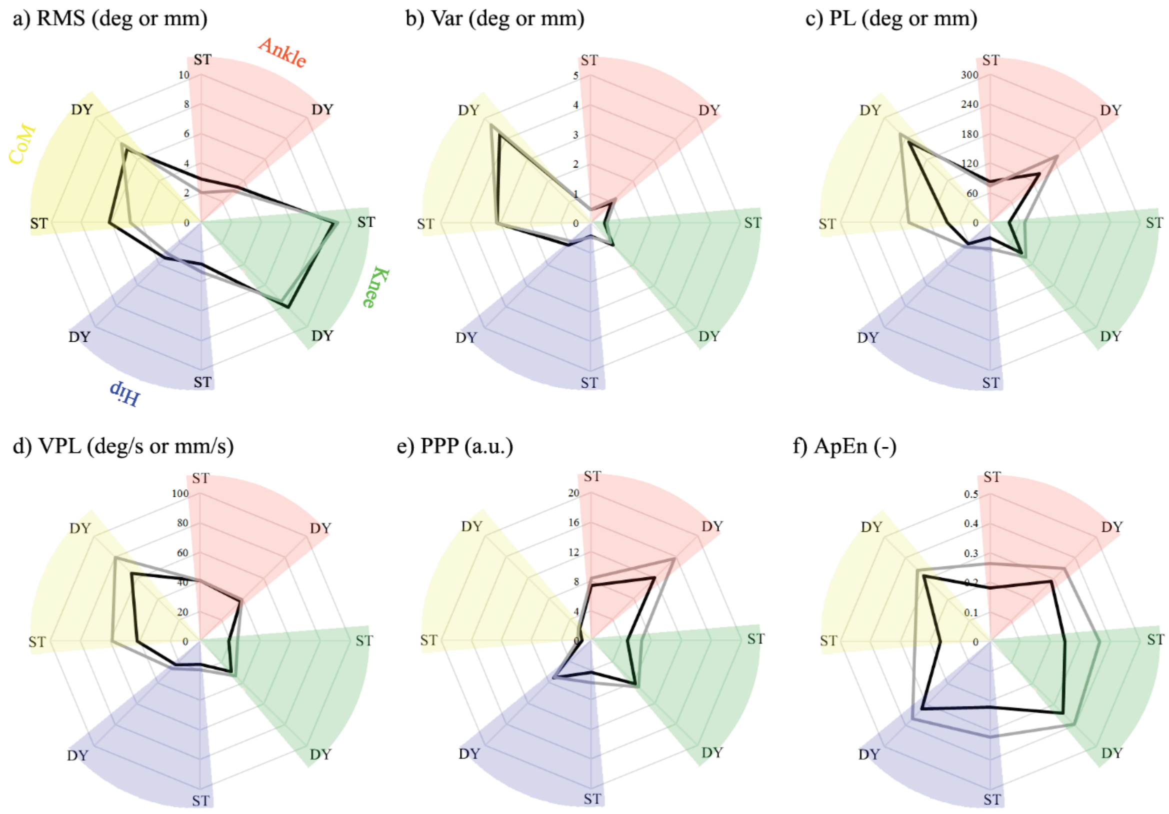
[40] Zech A., Steib S., Hentschke C., Eckhardt H., Pfeifer K., *Effects of Localized and General Fatigue on Static and Dynamic Postural Control in Male Team Handball Athletes*, Journal of Strength and Conditioning Research, 2012, 26 (4), https://doi.org/10.1519/JSC.0b013e31822dfbbb

Appendix

Table A1. Definition of the stability metrics used in the study for the generalized parameter x

Parameter	Definition	Formula	Dimension
Root mean square (RMS)	Arithmetic mean of the squares	$\sqrt{\frac{\Sigma_i x_i^2}{n}}$	cm or deg
Variability (Var)	Standard deviation (σ) of the parameter	$\sqrt{\frac{\Sigma_i (x_i - \bar{x})^2}{n}}$	cm or deg
Path length (PL)	Length of the path that a parameter (x) curve owns	$\Sigma_i \mid x_{i+1} - x_i \mid$	cm or deg
Velocity path length (VPL)	Path length of the parameter's first time derivative vs. time	$\Sigma_i \mid \dot{x}_{i+1} - \dot{x}_i \mid$	cm/s or deg/s
Phase plane portrait (PPP)	Planar standard deviation (σ_x, $\sigma_{\dot{x}}$) of the phase plane ($\dot{x}$ vs. x diagram)	$\sqrt{\sigma_x^2 + \sigma_{\dot{x}}^2}$	cm or deg
Approximate Entropy (ApEn)	Amount of regularity and unpredictability of fluctuations over time-series data	In ref [R1]	–
Short-term response slope (SRD)	Half of the slope in the linear regression before the critical point (CP)	$\frac{1}{2}\frac{\langle \Delta x^2 \rangle}{\Delta t}$ @ $\Delta t < CPx$	cm^2/s or deg^2/s

[R1] PINCUS S.M., GLADSTONE I.M., EHRENKRANZ R.A., *A regularity statistic for medical data analysis*, Journal of Clinical Monitoring and Computing, 1991, Oct. 1, 7 (4), 335–345.


a) RMS (deg or mm) b) Var (deg or mm) c) PL (deg or mm)

d) VPL (deg/s or mm/s) e) PPP (a.u.) f) ApEn (-)

Fig. A1. Polar representation of the stability metrics for the ankle, knee, and hip rotations and the CoM anterior-posterior excursion. The analysis includes nine metrics: a) RMS: The root mean square, b) Var: variability, c) PL: path length, d) VPL: velocity path length, e) PPP: phase plane portrait, f) ApEn: the approximate entropy