Journal of Biomechanics 110 (2020) 109983

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Repeatability of skin-markers based kinematic measures from a multi-segment foot model in walking and running

Alessandra B. Matias [a], Paolo Caravaggi [b], Alberto Leardini [b], Ulisses T. Taddei [a], Maurizio Ortolani [b], Isabel Sacco [a,*]

[a] Physical Therapy, Speech and Occupational Therapy Dept., School of Medicine, University of Sao Paulo, SP, Brazil
[b] Movement Analysis Laboratory, IRCCS Istituto Ortopedico Rizzoli, Bologna, Italy

ARTICLE INFO

Article history:
Accepted 1 August 2020

Keywords:
Foot kinematics
Skin-markers
Walking
Running
Repeatability
Errors

ABSTRACT

Skin-markers based multi-segment models are growing in popularity to assess foot joint kinematics in different motor tasks. However, scarce is the current knowledge of the effect of high-energy motor tasks, such as running, on the repeatability of these measurements. This study aimed at assessing and comparing the inter-trial, inter-session, and inter-examiner repeatability of skin-markers based foot kinematic measures in walking and running in healthy adults. The repeatability of 24 kinematic measures from an established multi-segment foot model were assessed in two volunteers during multiple barefoot walking and running trials by four examiners in three sessions. Statistical Parametric Mapping (1D-SPM) analysis was performed to assess the degree of shape-similarity between patterns of kinematic measurements. The average inter-trial variability across measurements (deg) was 1.0 ± 0.3 and 0.8 ± 0.3, the inter-session was 3.9 ± 1.4 and 4.4 ± 1.5, and the inter-examiner was 5.4 ± 2.3 and 5.7 ± 2.2, respectively in walking and running. Inter-session variability was generally similar between the two motor tasks, but significantly larger in running for two kinematic measures ($p < 0.01$). Inter-examiner variability was generally larger than inter-trial and inter-session variability. While no significant differences in frame-by-frame offset variability was detected in foot kinematics between walking and running, 1D-SPM revealed that the shape of kinematic measurements was significantly affected by the motor task, with running being less repeatable than walking. Although confirmation on a larger population and with different kinematic protocols should be sought, attention should be paid in the interpretation of skin-markers based kinematics in running across sessions or involving multiple examiners.

1. Introduction

The foot is a complex biomechanical structure with multiple degrees of freedom. In order to measure foot joint motion non-invasively, a large number of skin-markers based kinematic protocols have been implemented and reported in the literature (Leardini et al., 2019). Diagnosis of musculoskeletal pathologies (Khazzam et al., 2007; Rao et al., 2007; Chang et al., 2014; Deschamps et al., 2016) quantitative assessment of footwear and foot orthotics (Barton et al., 2011; Oosterwaal et al., 2011; Leardini et al., 2014; Bishop et al., 2016) and evaluation of sport tasks' performances (Arndt et al., 2007; Kelly et al., 2014; Takabayashi et al., 2018) are only few examples of the importance of these kinematic protocols across several research fields. Their applications have been further boosted by the sport biomechanics community, due to the increasingly large popularity of recreational running across age-groups and populations worldwide. Among these protocols, the capability to track the midfoot segment have helped increase the applications of the Rizzoli Foot Model (RFM) (Leardini et al., 2007; Deschamps et al., 2012b; Portinaro et al., 2014) also outside the clinical context (Leardini et al., 2019). Despite its extensive use in running biomechanics (Powell et al., 2013; Shih et al., 2014; Sinclair et al., 2014, 2015; Sterzing et al., 2015; Trudeau et al., 2017; Kelly et al., 2018; Langley et al., 2018), the repeatability of the RFM has thus far been reported for rotations of the main foot joints in walking only, and no repeatability of kinematic data in running has thus far been provided.

In fact, despite the large number of skin-markers based multi-segment foot models currently available, e.g. Kidder et al., 1996; Carson et al., 2001; Leardini et al., 2007; Bishop et al., 2013, few of these have been thoroughly tested for repeatability in standard gait-analysis tasks (Kidder et al., 1996; Carson et al., 2001; Leardini

* Corresponding author at: Rua Cipotânia, 51. Cidade Universitária, CEP: 05360-17 000, São Paulo, SP, Brazil.
E-mail address: icnsacco@usp.br (I. Sacco).

https://doi.org/10.1016/j.jbiomech.2020.109983
0021-9290/

et al., 2007; Bishop et al., 2013) and scarce is the current knowledge on the effects of high-energy activities, such as running, on measurements repeatability with respect to lower-energy locomotion such as walking. A larger repeatability helps increasing the statistical power and decreasing the minimal detectable difference when assessing group effects.

Physiological alterations in the execution of a motor task and errors in the methodology and instrumentation may both affect the variability of kinematic measurements (Newell and Slifkin, 1998). In addition to the variability in motor task execution (Bartlett et al., 2007), which is independent from the measuring system, the two main sources of variability in skin-markers based kinematic measurements are due to inconsistent markers' placement (Carson et al., 2001; Caravaggi et al., 2011), by different examiners or across sessions, and the soft tissue artifacts (Tranberg and Karlsson, 1998). Walking and running are both complex multiple degree of freedom motor tasks entailing motion of the foot and lower limb joints, thus are subjected to natural variability (Davids et al., 2003; Bartlett et al., 2007).

Different methodological approaches have been proposed to get better insight into within- and between- subjects' variability (Hunter et al., 2004; Mullineaux et al., 2004; Schwartz et al., 2004). Schwartz et al. (2004) suggested that within-subject, within-observer and between-observer errors of kinematic measurements can be identified beyond the natural variability of the motor task. However, scarce is the current understanding on how soft tissue artifacts affect skin-markers based foot kinematics in running compared to walking, therefore their effect on repeatability of these measurements is difficult to predict. In general, identifying the contribution of each source of variability in the kinematic measurement is not simple. Thus, in this study, the term "variability" will express the combination of the inherent motor task variability and the methodological sources of errors.

The main goal of this study was to assess the inter-trial, inter-session and inter-examiner repeatability of skin-markers based kinematic measurements of foot joints via the RFM in barefoot level walking and running. It was hypothesized that the repeatability of kinematic measurements would be lower in running compared to that in walking.

2. Methods

Two healthy subjects (subject A: female, 30 yrs, 57 kg, 1.54 m, Arch Index = 0.22, Foot Posture Index = +2; subject B: male, 26 yrs, 74 kg, 1.76 m, Arch Index = 0.26, Foot Posture Index = +3) were recruited in the study. The shank and foot were instrumented with 16 reflective skin-markers according to the RFM (Leardini et al., 2007; Portinaro et al., 2014) by four examiners in three sessions, one week apart (Schwartz et al., 2004). The RFM allows to measure rotation in the three anatomical planes between shank and foot (ShFo), shank and calcaneus (ShCa), calcaneus and midfoot (CaMi), midfoot and metatarsus (MiMe), calcaneus and metatarsus (CaMe) and first metatarsus and hallux (MeHa). Seven additional clinically-meaningful angles were calculated: F2G, the sagittal-plane inclination of the 1st metatarsal bone to the ground; S2G, the sagittal-plane inclination of the 2nd metatarsal bone to the ground; V2G, the sagittal-plane inclination of the 5th metatarsal bone to the ground; S2F, the transverse-plane divergence between 1st and 2nd metatarsal bones; S2V, the transverse-plane divergence between 5th and 2nd metatarsal bones, and MLA, the medial longitudinal arch angle. Repeatability of the 24 RFM kinematic measures was assessed via the inter-trial, inter-session and inter-examiner variability in accordance with Schwartz et al. (2004). Three out of the four examiners had extensive experience with the present marker – set protocol. The fourth examiner, familiar with gait analysis methods in general, was trained on this protocol just before starting the data collection.

In each session, the participants walked and ran barefoot at self-selected speed on an instrumented treadmill (AMTI, Watertown, MA). An eight-camera motion analysis system (Vicon, Oxford, England) collected 3D kinematic data at 200 Hz. Both subjects were deemed rearfoot strikers after visual assessment of videos from high-speed cameras (125 Hz). Foot markers trajectories were filtered with a Woltring low-pass filter (cutoff frequency = 10 Hz) and processed in Visual3D (C-Motion, Germantown, MD). Joint rotations were calculated using the Joint Coordinate System (Grood and Suntay, 1983) convention. The axes of each joint reference frame were defined as follows: sagittal plane rotations around axis z (medio-lateral); frontal plane around axis × (anterior-posterior); and transverse plane rotations around axis y (vertical). Ground reaction forces were recorded at 1000 Hz for gait cycle phases' determination. Data were normalized to 0–100% of stance phase.

The offset variability across measurements of each kinematic variable was determined according to Schwartz et al. (2004). This is calculated as the average - across normalized time duration - of the frame-by-frame standard deviation across trials, which were pooled as follows: inter-trial, across 24 groups (4 examiners*2 subjects*3 sessions) of 5 trials; inter-session, across 8 groups (4 examiners*2 subjects) of 15 trials; inter-examiner, across 2 groups (2 subjects) of 60 trials for each walking and running.

According to Shapiro-Wilk test, most of the offset variability of kinematic measures was not normally distributed ($p > 0.05$). Therefore, Wilcoxon signed rank test with Bonferroni-correction was used to find any significant difference in variability between walking and running Correlation analysis identified five independent variables of inter-session variability, thus an adjusted alfa = 0.01 was used when comparing intersession variability between walking and running. 1D-Statistical parametric mapping (1D-SPM) was used to assess repeatability of kinematic measurements in terms of full patterns (Pataky, 2010). This was achieved by comparing groups of 5 trials each across examiners and sessions. To assess inter-examiner repeatability, t-tests were used to perform 36 group-to-group comparisons for each kinematic measure: 6 comparisons*3 sessions*2 subjects. To assess inter-session repeatability, 24 comparisons were performed for each kinematic measure: 3 comparisons*4 examiners*2 subjects. In order to assess differences in the temporal pattern of measurements regardless of the initial offset, the joint rotations in bipedal standing posture recorded in each session for each examiner were removed from the corresponding kinematic data. According to the outcome of each group-to-group comparison, this was scored as follows: repeatable, if no statistical difference was found; largely repeatable, if the total suprathreshold cluster was less than 20% of the whole time interval; lowly repeatable, if the total suprathreshold cluster was between 21 and 99% of the whole time interval, and no repeatable if the suprathreshold cluster was equal to 100% of the time interval (see Fig. 1).

The study was approved by the Research and Ethics Committee of the School of Medicine, University of Sao Paulo (#031/15) and all participants gave informed consents prior to participation.

3. Results

For each kinematic measure, the inter-examiner offset variability was larger than the inter-session and the latter was larger than the inter-trial (Fig. 2). Respectively in walking and in running, the average inter-trial variability (deg, ±SD) across measurements was 1.0 ± 0.3 (range 0.5–1.6) and 0.8 ± 0.3 (0.3–1.4 deg), the inter-session was 3.9 ± 1.4 (1.9–7.4) and 4.4 ± 1.5 (2.1–7.3), and the

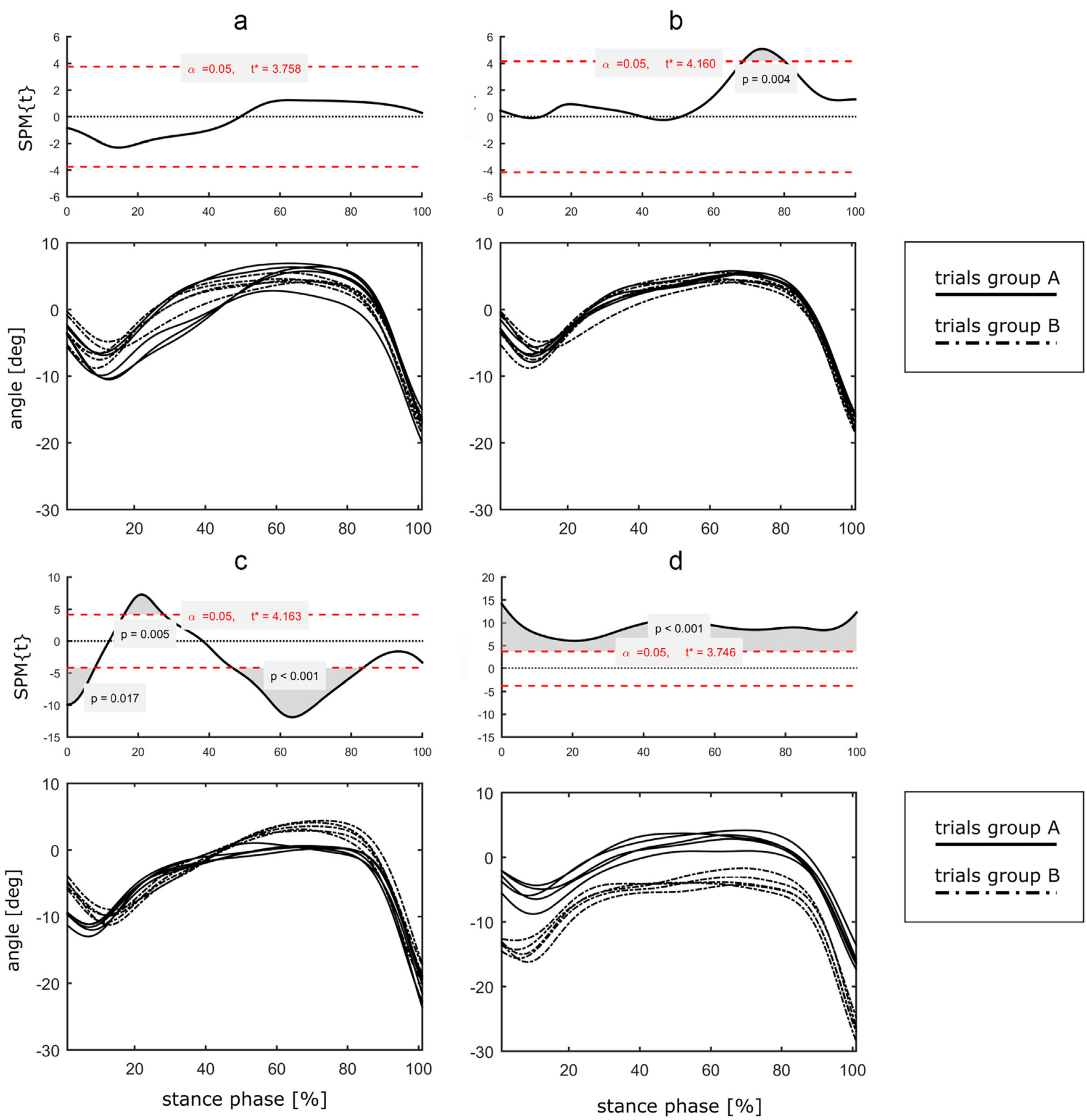

Fig. 1. Exemplary 1D-SPM comparisons between two groups of trials for sagittal plane motion between shank and calcaneus in walking. According to the outcome of the group-to-group comparison, kinematic data were classified as: (a) repeatable, when no difference was detected between the two groups of trials over stance duration; (b) largely repeatable, if the suprathreshold cluster was smaller than 20% of the stance duration; (c) lowly repeatable, if the suprathreshold cluster was between 20 and 99% of the stance duration, and (d) no repeatable, if the suprathreshold cluster was equal to 100% of the stance duration.

inter-examiner was 5.4 ± 2.3 (2.4–11.4) and 5.7 ± 2.2 (2.8–10.8). The largest inter-examiner variability was observed for sagittal-plane the calcaneus-metatarsus angle (CaMe-z) and first metatarsophalangeal joint rotations (MeHa), and the lowest for the sagittal-plane rotations of the shank-foot angle (ShFo-z) (Fig. 2). Wilcoxon signed rank test identified 9 kinematic measures with slightly larger inter-trial variability in walking compared to running ($p < 0.05$; range difference: 0.1–0.5 deg) and 2 kinematic measures with slightly larger inter-session variability in running ($p < 0.01$; range: 0.7–1.1 deg) (see Fig. 2).

The outcome of the repeatability assessment via 1D-SPM in walking and running is shown in Fig. 1. For each kinematic variable, it is reported the percentage of group-to-group comparisons, which resulted repeatable, largely repeatable, lowly repeatable and no repeatable (Fig. 3). In walking, most kinematic measures were repeatable or largely repeatable. Only motion between midfoot and calcaneus (CaMi), and transverse plane rotations between metatarsus and midfoot (MiMe-y) were, for most comparisons, lowly repeatable inter-examiner and inter-session. In running, all variables were mostly low or no repeatable (see Fig. 3).

4. Discussion

Repeatability of kinematic measurements should be acknowledged or carefully assessed in order to properly design a study in terms of sample size and to allow correct interpretation of intra-

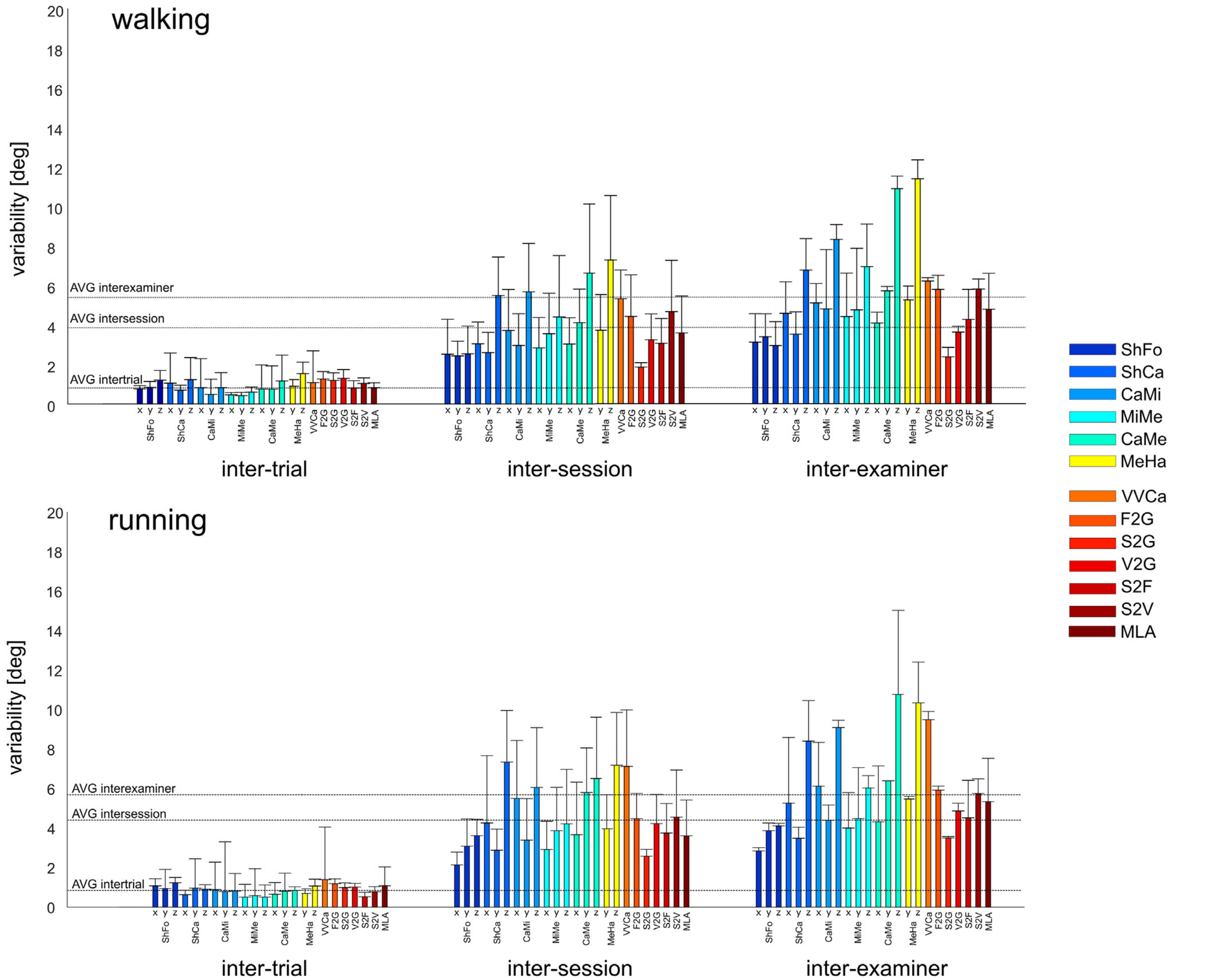

Fig. 2. Inter-trial, inter-session and inter-examiner offset variability of 24 kinematic measures from the Rizzoli Foot Model during stance phase of walking (top) and running (bottom). Average offset variability across all kinematic variables in the same variability group are shown as dotted straight line.

and inter-subject differences. The offset variability in the main foot joint rotations and in the medial longitudinal arch deformation calculated here in walking were consistent with those reported previously using the same kinematic protocol (Caravaggi et al., 2011, 2019). Moreover, similar to what reported before, inter-examiner variability was larger than inter-trial and inter-session, both in walking and running (Caravaggi et al., 2011, 2019).

As far as motor task effect is considered, inter-trial variability was lower for nine kinematic measures, and inter-session variability was larger for two kinematic measures in running with respect to walking. Although for most measures walking and running showed similar offset variability, the repeatability assessment of patterns via 1D-SPM analysis revealed that skin-markers based foot joint motion is highly variable across examiners and sessions. While it is difficult to tell apart the contribution of the natural motor task variability from the errors due to skin-markers placement and skin-motion artifacts on the observed low repeatability of kinematic patterns, running showed a larger variability of skin-markers based foot joints motion with respect to walking, thus confirming the hypothesis of our study. This information should be accounted for when comparing kinematic data between groups (e.g. pathological vs. healthy control) as shape differences in the patterns– such as different normalized time-points of minimum-maximum joint rotations - may not indicate kinematic alterations due to the pathology or any other variable analyzed, but could be the consequence of measurements' variability, including errors in markers' placement across sessions.

Similar to what observed in this study, there seem to be a significant examiner effect on the repeatability of some kinematic measurements, such as the S2F angle and the rotations involving calcaneus and midfoot (Caravaggi et al., 2011; Deschamps et al., 2012a). The largest variability inter-session was found for sagittal-plane rotations between shank and calcaneus, whereas the largest inter-examiner variability for the calcaneus-metatarsus joint, in both walking and running. These results are consistent with what reported by Caravaggi et al. (2011), suggesting that small differences in the position of the markers on the calcaneus could result in large variability of the frame-by-frame measurements entailing this segment. The variability in frontal-plane alignment of the calcaneus (VVCa), sagittal-plane rotation between calcaneus and metatarsus (CaMe-z) and between metatarsus and hallux (MeHa-z) were larger than 5 deg for both walking and running, thus particular attention should be paid when assessing those measures. Our findings further stress the

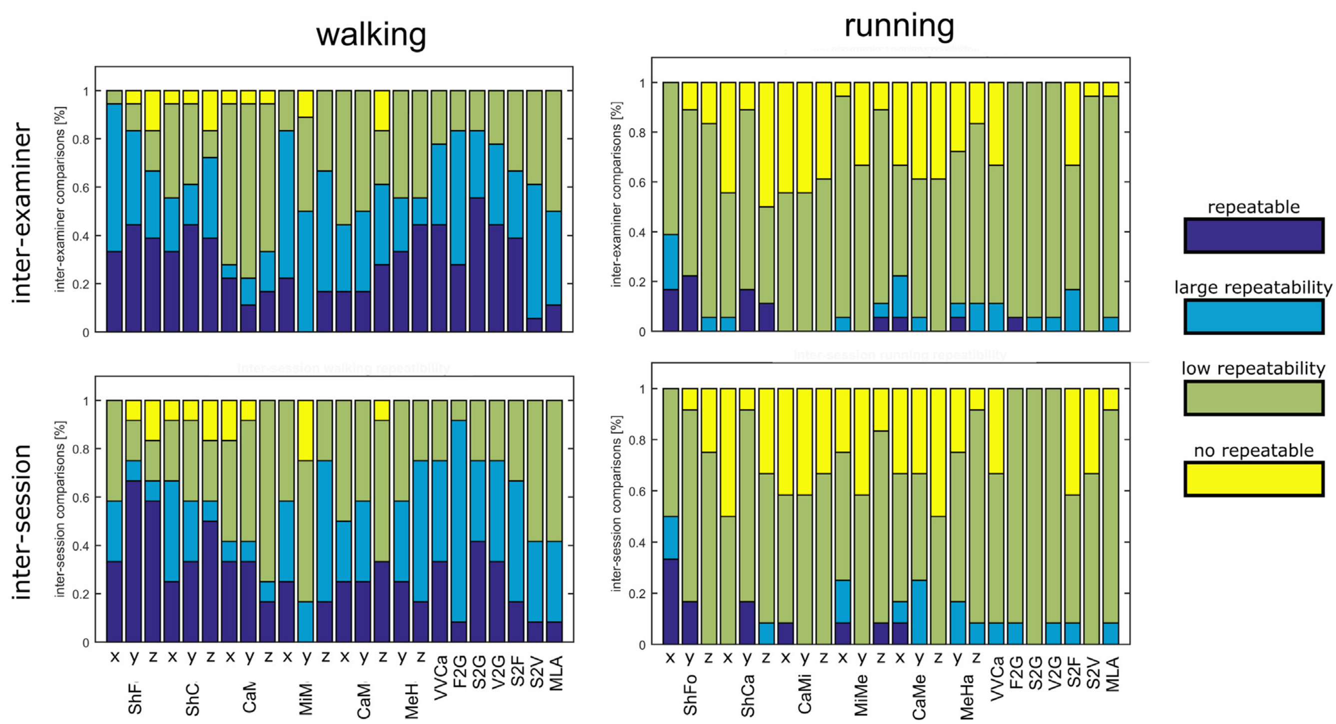

Fig. 3. For each kinematic measure, percentage of group-to-group comparisons, which were deemed as repeatable, largely repeatable, lowly repeatable and no repeatable inter-session and inter-examiner for the two motor tasks (see Fig. 1).

need for experienced examiners in markers positioning especially when collecting data in different sessions.

While subjects walked and ran at their self-selected comfortable speed on a treadmill to minimize the natural motor task variability (Dingwell et al., 2001; Jordan and Newell, 2008; Wheat et al., 2005), the present analysis could not distinguish the source of variability in the measurements. As expected, natural motor task variability could be confused with experimental error. Estep et al. (2018) have reported larger natural variability in running with respect to walking, which may have contributed to the lower repeatability of treadmill running kinematic measurements observed in this study. According to Schwartz et al. (2004) the inter-trial variability could be used as an indicator of the motor task natural variability, and to assess extrinsic variability. Further studies should therefore be sought to estimate the weight of the motor task natural variability with respect to other sources of errors.

According to the results of this study, shape-similarity of kinematic patterns appear to be highly affected by the motor task, with running being less repeatable than walking. Although confirmation on a larger population and with different kinematic protocols should be sought, attention should be paid in the interpretation of skin-markers based kinematics in running across sessions or involving multiple examiners.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

State of São Paulo Research Foundation (FAPESP) funded the project (2015/14810-0), the fellowship of Caravaggi (2017/23975-8) and Matias (2016/17077-4 and 2017/26844-1). I. C.N. Sacco is a fellow of the National Council for Scientific and Technological Development (CNPq) (Process: 304124/2018-4). Taddei was awarded by Agency Coordination of Improvement of Higher Education Personnel (CAPES, financial code 001).

References

Arndt, A., Wolf, P., Liu, A., Nester, C., Stacoff, A., Jones, R., Lundgren, P., Lundberg, A., 2007. Intrinsic foot kinematics measured in vivo during the stance phase of slow running. J. Biomech. 40, 2672–2678.

Bartlett, R., Wheat, J., Robins, M., 2007. Is movement variability important for sports biomechanists?. Sport. Biomech. 6, 224–243.

Barton, C.J., Levinger, P., Webster, K.E., Menz, H.B., 2011. Walking kinematics in individuals with patellofemoral pain syndrome: a case–control study. Gait Posture 33, 286–291.

Bishop, C., Arnold, J.B., May, T., 2016. Effects of taping and orthoses on foot biomechanics in adults with flat-arched feet. Med. Sci. Sports Exerc. 48, 689–696.

Bishop, C., Paul, G., Thewlis, D., 2013. The reliability, accuracy and minimal detectable difference of a multi-segment kinematic model of the foot-shoe complex. Gait Posture 37, 552–557.

Caravaggi, P., Benedetti, M.G., Berti, L., Leardini, A., 2011. Repeatability of a multi-segment foot protocol in adult subjects. Gait Posture 33, 133–135.

Caravaggi, P., Matias, A.B., Taddei, U.T., Ortolani, M., Leardini, A., Sacco, I.C.N., 2019. Reliability of medial-longitudinal-arch measures for skin-markers based kinematic analysis. J. Biomech. 88, 180–185.

Carson, M.C.C., Harrington, M.E., Thompson, E., O'Connor, J.J.J., Theologis, T.N.N., 2001. Kinematic analysis of a mulit-segment foot model for research and clinical applications: a repeatability analysis. J. Biomech. 34, 1299–1307.

Chang, R., Rodrigues, P.A., Van Emmerik, R.E.A., Hamill, J., 2014. Multi-segment foot kinematics and ground reaction forces during gait of individuals with plantar fasciitis. J. Biomech. 47, 2571–2577.

Davids, K., Glazier, P., Araujo, D., Bartlett, R., 2003. Movement systems as dynamical systems: the functional role of variability and its implications for sports medicine. Sport. Med. 33, 245–260.

Deschamps, K., Dingenen, B., Pans, F., Bavel, I.V., Arnoldo, G., Staes, F., Van Bavel, I., Matricali, G.A., Staes, F., 2016. Effect of taping on foot kinematics in persons with chronic ankle instability. J. Sci. Med. Sport 19, 541–546.

Deschamps, K., Staes, F., Bruyninckx, H., Busschots, E., Jaspers, E., Atre, A., Desloovere, K., 2012a. Repeatability in the assessment of multi-segment foot kinematics. Gait Posture 35, 255–260.

Deschamps, K., Staes, F., Bruyninckx, H., Busschots, E., Matricali, G.A., Spaepen, P., Meyer, C., Desloovere, K., 2012b. Repeatability of a 3D multi-segment foot model protocol in presence of foot deformities. Gait Posture 36, 635–638.

Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R., Sternad, D., 2001. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. J. Biomech. Eng. 123, 27–32.

Estep, A., Morrison, S., Caswell, S., Ambegaonkar, J., Cortes, N., 2018. Differences in pattern of variability for lower extremity kinematics between walking and running. Gait Posture 60, 111–115.

Grood, E.S., Suntay, W.J., 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J. Biomech. Eng. 105, 136–144.

Hunter, J.P., Marshall, R.N., McNair, P., 2004. Reliability of biomechanical variables of sprint running. Med. Sci. Sports Exerc. 36, 850–861.

Jordan, K., Newell, K.M., 2008. The structure of variability in human walking and running is speed-dependent. Exerc. Sport Sci. Rev. 36, 200–204.

Kelly, L.A., Cresswell, A.G., Racinais, S., Whiteley, R., Lichtwark, G., 2014. Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch. J. R. Soc. Interface 11, 20131188.

Kelly, L.A., Farris, D.J., Lichtwark, G.A., Creswell, A.G., 2018. The influence of foot-strike technique on the neuromechanical function of the foot. Med. Sci. Sports Exerc. 50, 98–108.

Khazzam, M., Long, J.T., Marks, R.M., Harris, G.F., 2007. Kinematic changes of the foot and ankle in patients with systemic rheumatoid arthritis and forefoot deformity. J. Orthop. Res. 25, 319–329.

Kidder, S.M., Abuzzahab, F.S., Harris, G.F., Johnson, J.E., 1996. A system for the analysis of foot and ankle kinematics during gait. IEEE Trans. Rehabil. Eng. 4, 25–32.

Langley, B., Cramp, M., Morrison, S.C., 2018. The influence of running shoes on inter-segmental foot kinematics. Footwear Sci., 1–11

Leardini, A., Benedetti, M.G., Berti, L., Bettinelli, D., Nativo, R., Giannini, S., 2007. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. Gait Posture 25, 453–462.

Leardini, A., Caravaggi, P., Theologis, T., Stebbins, J., 2019. Multi-segment foot models and their use in clinical populations. Gait Posture 69, 50–59.

Leardini, A., O'Connor, J.J., Giannini, S., 2014. Biomechanics of the natural, arthritic, and replaced human ankle joint. J. Foot Ankle Res. 7, 8.

Mullineaux, D.R., Clayton, H.M., Gnagey, L.M., 2004. Effects of offset normalizing techniques on variability in motion analysis data. J. Appl. Biomech. 20, 177–184.

Newell, K.M., Slifkin, A.B., 1998. Motor Behavior and Human Skill: A Multidisciplinary Approach. Human Kinetics, Champaign, IL.

Oosterwaal, M., Telfer, S., Tørholm, S., Carbes, S., Van Rhijn, L.W., Macduff, R., Meijer, K., Woodburn, J., 2011. Generation of subject-specific, dynamic, multisegment ankle and foot models to improve orthotic design: A feasibility study. BMC Musculoskelet. Disord. 12, 256.

Pataky, T.C., 2010. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. J. Biomech. 43, 1976–1982.

Portinaro, N., Leardini, A., Panou, A., Monzani, V., Caravaggi, P., 2014. Modifying the Rizzoli foot model to improve the diagnosis of pes-planus: Application to kinematics of feet in teenagers. J. Foot Ankle Res. 7, 754.

Powell, D.W., Williams, D.S.B., Butler, R.J., 2013. A comparison of two multisegment foot models in high-and low-arched athletes. J. Am. Podiatr. Med. Assoc. 103, 99–105.

Rao, S., Saltzman, C., Yack, H.J., 2007. Segmental foot mobility in individuals with and without diabetes and neuropathy. Clin. Biomech. 22, 464–471.

Schwartz, M.H., Trost, J.P., Wervey, R.A., 2004. Measurement and management of errors in quantitative gait data. Gait Posture 20, 196–203.

Shih, Y., Ho, C.-S., Shiang, T.-Y., 2014. Measuring kinematic changes of the foot using a gyro sensor during intense running. J. Sports Sci. 32, 550–556.

Sinclair, J., Chockalingam, N., Vincent, H., 2014. Gender differences in multi-segment foot kinematics and plantar fascia strain during running. Foot Ankle Online J. 7.

Sinclair, J., Isherwood, J., Taylor, P.J., 2015. The effects of orthotic intervention on multisegment foot kinematics and plantar fascia strain in recreational runners. J. Appl. Biomech. 31, 28–34.

Sterzing, T., Custoza, G., Ding, R., Cheung, J.T.-M., 2015. Segmented midsole hardness in the midfoot to forefoot region of running shoes alters subjective perception and biomechanics during heel-toe running revealing potential to enhance footwear. Footwear Sci. 7, 63–79.

Takabayashi, T., Edama, M., Yokoyama, E., Kanaya, C., Kubo, M., 2018. Quantifying coordination among the rearfoot, midfoot, and forefoot segments during running. Sport. Biomech. 17, 18–32.

Tranberg, R., Karlsson, D., 1998. The relative skin movement of the foot: a 2-D roentgen photogrammetry study. Clin. Biomech. 13, 71–76.

Trudeau, M.B., Jewell, C., Rohr, E., Fischer, K.M., Willwacher, S., Brueggemann, G.-P., Hamill, J., 2017. The calcaneus adducts more than the shoe's heel during running. Footwear Sci. 9, 79–85.

Wheat, J.S., Baltzopoulos, V., Milner, C.E., Bartlett, R.M., Tsaopoulos, D., 2005. Coordination variability during overground, treadmill and treadmill-on-demand running. In: ISBS - Conference Proceedings Archive, pp. 2003–2006.