Reporting guidelines for running biomechanics and footwear studies using three-dimensional motion capture

Editorial

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Word count: 2720 words

Number of tables and figures: 0

Twitter text: Editorial – Reporting guidelines for running biomechanics and footwear studies using 3D motion capture

Background

Running shoes act as an interface between the foot and the ground and play a central role in running. Running shoes are constantly evolving [1, 2], as is the research on running biomechanics and footwear [3-5]. Experts agree that comfort, injury prevention, and performance are important factors to consider in the design and manufacturing of running footwear [6]; however, these topics are often complex to investigate due to their multifactorial [7-9], individualised [10, 11], or subjective [7] nature with no clear evidence-based direction for footwear prescription [3, 12].

The running footwear literature seems in a constant state of debate, whether with regards to the role of footwear in enhancing performance [13], reducing the risk of injury [3], or promoting a more natural style of running [1]. In addition, the inconsistency in footwear taxonomy and how footwear properties are measured and reported [14] make it challenging to derive strong or meaningful inferences from the running biomechanics and footwear literature.

It is nonetheless clear that footwear can affect running biomechanics with performance [15-17] and injury [16, 18] ramifications. It is also clear that there is a replication and confidence of results crisis in exercise science and sports biomechanics [19, 20], again challenging our capability as scientists to make strong inferences from the scientific literature. Transparent and clear reporting of methods and adopting strong methodological procedures are part of the solution. The Standardization and Terminology Committee of the International Society of Biomechanics (ISB) has published several recommendations regarding definitions and reporting standards to guide the biomechanics community and enhance communication among researchers and practitioners [21-25]. The Editorial Board of Sports Biomechanics endorses and encourages all authors to consult these recommendations. The purpose of this editorial is not to supersede the ISB recommendations. Rather, our purpose is to highlight some key considerations for running biomechanics and footwear research involving three-dimensional (3D) motion capture technology. Although the considerations here focus on 3D motion capture technology specifically, these principles extend to other kinematics or kinetics data collection methods, which can be used as general methodological and reporting guidelines for running biomechanics and footwear research. The scope of this editorial is not to prescribe methodological approaches, market sets, models, or data processing approaches. Rather, our aim is to outline a series of considerations and recommendations for running biomechanics and footwear research involving 3D motion capture with regards to the transparent and clear reporting of methods, to encourage opportunities for replication studies in this topical area of research. Replication studies are needed to build standards of cumulative evidence, especially in the areas of footwear prescription and injury prevention [26].

Sampling rates

The Nyquist sampling theory recommends using sampling rates that are at least twice the highest frequency of the signal of interest. In practice, researchers in biomechanics typically sample at 5 to 10 times the highest frequency of the signal of interest to ensure the entire signal content is captured whilst minimising noise and data redundancy. For running, the recommended sample rates for the 3D kinematics are 100 to 200 Hz [27], although sampling rates of 240 Hz [28, 29], 250 Hz [30], and 300 Hz [17] have been reported, as well as up to 500 Hz to examine soft tissue vibration whilst running [31]. The same theory applies to the measurement of ground reaction forces (GRFs), where a minimum sampling rate of 500 Hz has been recommended for sporting movements involving impacts [32]. A sampling rate of 1000 Hz is a more common choice than 500 Hz in sports [33] and is typically used in running biomechanics and footwear research [34-37], although higher sampling rates (e.g., 2000 – 2400 Hz) have also been reported [18, 31, 38]. Generally, the sampling rate of GRF data is a multiple of the sampling rate of the kinematic data, often set at four times that of the kinematic one. We recommend researchers confirm their minimum sampling frequency requirements before starting data collection, and if the selected equipment does not support the minimum sampling requirements, to select more suitable measurement equipment. Up sampling data is not advised, although validated signal processing techniques can be used to reconstruct specific missing features related to higher frequency parameters of signals, for example, rearfoot motion or impact peak of the GRF [39]. If such signal processing techniques are applied, it is important that this is clearly stated in the manuscript, and that the processed data meet the prerequisite assumptions (e.g., circular continuity).

Data processing

There is no standard data filtering approach used across the biomechanics literature, with the selection shown to affect biomechanical data and their interpretation [21, 40-43]. Among the many data processing methods, such as spline, polynomial, and time domain filtering, the

Butterworth digital filter is one of the most commonly used for gait analysis. Typically, running kinematic data are filtered using a low cut-off frequency (6 to 10 Hz), although it is argued that relevant events take place at frequencies in the 12 to 20 Hz range [27]. The latter justifies the presence and use of higher kinematic data cut-off frequencies in running research [44, 45]. Cut-off frequencies no lower than 15 Hz are recommended for the 3D motion capture of running biomechanics and footwear to avoid attenuating high-frequency impact phenomena components of signals [46, 47], especially when the more distal segments of the lower extremities are of interest where frequencies are higher. In addition, when calculating moments, some researchers recommend using the same cut-off frequencies for kinematic and kinetic data filtering [40, 48, 49]. However, depending on the research question and variables of interest, such as when examining impact forces or peak joint moments, matching kinematic and kinetic cut-off frequencies might be inappropriate [21, 50]. In such instances, employing higher cut-off frequencies for kinetic than kinematic data or examining unfiltered GRF data can be warranted. Filtering on running data is generally reasonable as the motion is very rhythmic, harmonic, and repeatable, and we can assume that sudden spikes, troughs, and signals outside the expected range are unwanted noise. However, the appropriateness of filtering sprinting biomechanics data, particularly when the start is involved, needs careful consideration. Filtering might remove sudden spikes and troughs that are biomechanically relevant and representative of the sprinting movement.

There are various approaches to selecting data processing parameters, with none consistently outperforming others when applied across a range of datasets or research applications [51]. Examples include, but are not limited to, noise identification through power analyses, frequency selection corresponding to a specific percentile of the cumulative power of the original signal, use of regression models based on sampling frequencies [52], or simply the selection of data processing methods to be consistent with previous studies. Common approaches in gait analysis to selecting cut-off frequencies include selecting one that maintains 99% of the data [53] or performing a residual analysis [54]. In the latter approach, differences between filtered and unfiltered signals across a range of cut-off frequencies are examined, with the frequency that minimises both signal distortion and noise being chosen [54]. Ultimately, it is important for authors to provide a justification for their choice of filters and cut-off frequencies.

Sometimes, running biomechanical data clip due to limitations in the measurement range of the equipment, which is not ideal as signal clipping suggests that the equipment is unable to fully capture the underlying movement. Removing clipped trials or steps is one approach commonly applied to deal with this issue, and authors are encouraged to transparently indicate how many trials and steps were disregarded for this reason. Another approach to dealing with clipped signals involves using curve-fitting techniques to estimate the missing data points, which should be clearly stated in the methods section and accompanied by analysis of the validity of the approach confirmed on unclipped data.

Reliability

Reliability of running 3D kinematic measures are superior within-days than between-days due to variations in marker placement in addition to system errors, biological variability, and skin movement artefacts [55]. The additional variability in 3D kinematics data observed between days has implications for comparing the effect of footwear on running biomechanics within individuals. Hence, most studies examining the effect of footwear on running biomechanics perform data collection on the same day to limit between-day variability in marker positioning. More recent studies, however, indicate good to excellent between-day reliability of discrete kinematic measures from 3D motion analysis of treadmill running gait except at toe off, with sagittal and frontal kinematics generally more reliable than transverse plane kinematics [56]. It can therefore be justifiable and possible to assess the effect of footwear on different days when marker placement is consistent, particularly when the same experienced investigator places markers [57] or a marker repositioning device is used [36]. There are numerous benefits of conducting testing on different days, such as longitudinal tracking of running form over time and minimising fatigue if several pairs of running shoes, intense running, or prolonged running bouts are examined. These reliability studies provide insights regarding the minimal detectable change from 3D motion analysis of running gait with ramifications towards data interpretation as well. For example, based on a between-day repeatability study, the minimal detectable change for knee flexion/extension, abduction/adduction, and internal/external rotation angles at touch-down is 6.9°, 2.5°, and 8.1°, respectively [56]. Hence, authors should consider these factors when designing and interpreting results from studies examining the effect of footwear (or any other intervention) on running biomechanics. In the presence of repeated trials, authors are encouraged to report within-day reliability of measures, both in absolute (e.g., standard error of measurement) and relative (e.g., intraclass correlation coefficients) terms. Readers are directed to other published work for more information on reliability and minimal detectable change measures in sport science and medicine [58-61].

Calibration, marker, and model considerations

The reliability of kinematic waveforms from running trials is comparable between anatomical and functional calibration methods [62], although calibration methods themselves can considerably affect running kinematic waveforms and discrete parameters [38, 63]. Hence, authors should describe their calibration methods. Similarly, marker sets and models used can affect biomechanical measures [64-67]. For example, using a one-segment compared to a multi-segment foot model can lead to opposite ankle kinematic results [68]. There are close to 40 multi-segment foot models reported in over 100 studies examining clinical populations, but few have undergone validation [63]. When modelling the foot, it is crucial that researchers clearly define the bony landmarks used for modelling, which segments are being modelled and how, the reference system or systems in use, the foot position during calibration, and any off-sets used in calculating kinematic parameters [23]. Researchers should also include definitions of joint centres and marker clusters, if used, to track the dynamic motion of the foot. In addition, consistency in the terminology and clear definitions of the reported joint angles is crucial for further interpretation of results, such as specifying whether computations are based on Cardan angles with a certain order of rotation, helical angles, or projection angles. Authors are encouraged to consult the ISB recommendations for further detail on skin marker-based multi-segment foot kinematics [23]. Similarly, when reporting joint kinetic parameters, authors should endeavour to employ appropriate mechanical terms and report their modelling approach [69], including body segment inertial parameter or anthropometric data sources [21].

Marker placement in the foot region is a topic that all running biomechanics and footwear researchers need to consider carefully. In running research involving footwear, researchers have two main options:

1) Position markers directly onto the skin, which typically involves modifying footwear and/or cutting holes in shoes; or

2) Position markers directly onto the shoes based on the underlying bony landmarks of the foot.

In either case, researchers and clinicians alike should understand that neither skin nor shoe markers reflect the underlying bone movements. Both skin [70] and shoe [71, 72] markers tend to overestimate motion compared to bone-pin markers. Moreover, markers placed on shoes have been reported to both underestimate [37, 73, 74] and overestimate [75, 76] motion compared to markers placed on the skin. Hence, contrasting the biomechanical parameters obtained using different marker placement methods, such as skin versus shoe marker kinematics, should be done with caution. Altogether, these results indicate that shoe markers primarily describe how the shoe moves; and although skin markers might provide a better indication of the underlying bone movement [37, 75], skin markers are susceptible to skin movement artefacts and errors [70, 77]. Readers interested in the topic of shoe versus skin mounted markers are encouraged to consult Arnold and Bishop's [81] broad review.

Again, our purpose is not to recommend specific calibration methods, marker sets, or models for use in running and footwear research, but rather to raise awareness regarding the impact that variations in calibration methods, marker sets, or models can exert on biomechanical outcomes. If these aspects are unreported or incompletely reported, it becomes quasi impossible to replicate studies, make valid inferences, or generalise findings. Authors should select calibration methods, marker sets, and models based on their needs, study aims, population, key outcome measures, and cost-benefit analysis of the various available options. In all cases, authors are encouraged to clearly describe the calibration method, marker set, and models used, provide a scientific justification, and ideally, present reliability and validity information.

Footwear considerations

Modifying footwear to place the markers on the skin instead of the shoe can compromise the integrity and properties of shoes [78, 79]. Studies in this area indicate that holes larger than 1.7 x 2.5 cm affect shoe integrity [79], yet holes smaller than 2.5 cm can restrict marker movement [80]. Researchers cutting holes in footwear to place markers directly onto the skin must do so with extreme care and precision, and should report hole size and shape as well as attempt to assess footwear properties and integrity pre and post modifications. Noteworthy is that none of this research considers the effect of hole size on the integrity of different footwear types (e.g., minimal versus maximal shoes) or shoe size. Given that foot anthropometry is highly individualised [81-83], holes cut in footwear on the basis of one participant's foot anatomy is likely unsuitable for another participant. Furthermore, researchers and clinicians often examine biomechanics of runners wearing their own shoes [10, 84, 85], wherein it becomes inappropriate to cut holes in shoes. Researchers placing markers on shoes can do so with relatively good accuracy and precision when palpating the underlying bony landmarks [86], although must pay particular attention to repositioning markers at the exact location between trials or footwear conditions given how small differences in marker positioning can substantially affect outcomes [35]. Furthermore, it is worth acknowledging that shoe type and technology can compromise the accuracy of marker positioning. For example, conventional running shoes usually contain a heel post, making it difficult to palpate the underlying calcaneus (heel) bone and position markers accurately. In addition, the fit of the shoe and the lacing will play a role in how well the motion of the shoe represents the motion of the foot.

Recommendations for three-dimensional motion capture reporting standards

Submissions to Sports Biomechanics in the area of running biomechanics and footwear using 3D motion capture technology are encouraged to include the following information in original research submissions to the journal:

- Data sampling frequency and processing procedures (e.g., interpolation, smoothing, and filtering), ideally with justification, including gait cycle event definitions;

- Motion capture system and software (version, model, company, origin), number of cameras, system calibration method, and measurement volume. Authors are encouraged to provide information regarding the accuracy of their set-up, such as the average residual and standard deviation of a known measurement length;

- Marker placement, 3D biomechanical model or models, participant-specific calibration method (e.g., static vs functional), coordinate systems, and methods for obtaining biomechanical parameters, such as joint centres, body segments, joint angles, and body segment inertial parameters. Any modifications or adaptations to original marker sets, models, conventions, or definitions should be justified and explained in sufficient detail to enable replication. If holes are cut in shoes or footwear are modified to place makers directly on the skin, authors should provide a figure of the shoes with holes and foot/shoe marker placements, report hole dimensions and shapes, as well as the potential influence of modifications on footwear properties and integrity;

- Reliability and validity of methods, such as the minimal detectable change of key parameters. Examining the reliability of marker placement and kinematics (and other biomechanical) data in-house is encouraged to support findings.

Declaration of interest statement

The authors report there are no competing interests to declare.

References

1. Davis, I.S., *The re-emergence of the minimal running shoe.* The Journal of Orthopaedic and Sports Physical Therapy, 2014. **44**(10): p. 775-784. doi: https://doi.org/10.2519/jospt.2014.5521.
2. Bermon, S., *Evolution of distance running shoes: performance, injuries, and rules.* The Journal of Sports Medicine and Physical Fitness, 2021. **61**(8): p. 1073-1080. doi: https://doi.org/10.23736/s0022-4707.21.12728-8.
3. Malisoux, L. and D. Theisen, *Can the "appropriate" footwear prevent injury in leisure-time running? Evidence versus beliefs.* Journal of Athletic Training, 2020. **55**(12): p. 1215-1223. doi: https://doi.org/10.4085/1062-6050-523-19.
4. Patoz, A., et al., *There is no global running pattern more economic than another at endurance running speeds.* International Journal of Sports Physiology and Performance, 2022: p. 1-4. doi: https://doi.org/10.1123/ijspp.2021-0345.
5. Nigg, B.M., S. Cigoja, and S.R. Nigg, *Effects of running shoe construction on performance in long distance running.* Footwear Science, 2020. **12**(3): p. 133-138. doi: https://doi.org/10.1080/19424280.2020.1778799.
6. Honert, E.C., et al., *Shoe feature recommendations for different running levels: A Delphi study.* PLoS One, 2020. **15**(7): p. e0236047. doi: https://doi.org/10.1371/journal.pone.0236047.

7. Menz, H.B. and D.R. Bonanno, *Footwear comfort: A systematic search and narrative synthesis of the literature.* Journal of Foot and Ankle Research, 2021. **14**(1): p. 63. doi: 10.1186/s13047-021-00500-9.

8. Esculier, J.-F., et al., *A contemporary approach to patellofemoral pain in runners.* Journal of Athletic Training, 2020. **55**(12): p. 1206-1214. doi: https://doi.org/10.4085/1062-6050-0535.19.

9. Barnes, K.R. and A.E. Kilding, *Running economy: Measurement, norms, and determining factors.* Sports Medicine-Open, 2015. **1**(8): p. 1-15. doi: https://doi.org/10.1186/s40798-015-0007-y.

10. Hébert-Losier, K., et al., *Metabolic and performance responses of male runners wearing 3 types of footwear: Nike Vaporfly 4%, Saucony Endorphin racing flats, and their own shoes.* Journal of Sport and Health Science, 2020: p. S2095-2546(20)30163-0. doi: https://doi.org/10.1016/j.jshs.2020.11.012

11. Moore, I.S., *Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy.* Sports Medicine, 2016. **46**(6): p. 793-807. doi: https://doi.org/10.1007/s40279-016-0474-4.

12. Richards, C.E., P.J. Magin, and R. Callister, *Is your prescription of distance running shoes evidence-based?* British Journal of Sports Medicine, 2009. **43**(3): p. 159-162. doi: https://doi.org/10.1136/bjsm.2008.046680.

13. Burns, G.T. and N. Tam, *Is it the shoes? A simple proposal for regulating footwear in road running.* British Journal of Sports Medicine, 2020. **54**(8): p. 439-440. doi: https://doi.org/10.1136/bjsports-2018-100480.

14. Ramsey, C.A., et al., *"How are running shoes assessed? A systematic review of characteristics and measurement tools used to describe running footwear".* Journal of Sports Sciences, 2019. **37**(14): p. 1617-1629. doi: https://doi.org/10.1080/02640414.2019.1578449.

15. Joubert, D.P. and G.P. Jones, *A comparison of running economy across seven highly cushioned racing shoes with carbon-fibre plates.* Footwear Science, 2022: p. 1-13. doi: https://doi.org/10.1080/19424280.2022.2038691.

16. Sun, X., et al., *Systematic review of the role of footwear constructions in running biomechanics: Implications for running-related injury and performance.* Journal of Sports Science and Medicine, 2020. **19**(1): p. 20-37.

17. Hébert-Losier, K., et al., *Kinematics of recreational male runners in "super", minimalist and habitual shoes.* Journal of Sports Sciences, 2022: p. 1-10. doi: https://doi.org/10.1080/02640414.2022.2081767.

18. Malisoux, L., et al., *Spatiotemporal and ground-reaction force characteristics as risk factors for running-related injury: A secondary analysis of a randomized trial including 800+ recreational runners.* The American Journal of Sports Medicine, 2022. **50**(2): p. 537-544. doi: https://doi.org/10.1177/03635465211063909.

19. Knudson, D., *Confidence crisis of results in biomechanics research.* Sports Biomechanics, 2017. **16**(4): p. 425-433. doi: https://doi.org/10.1080/14763141.2016.1246603.

20. Caldwell, A.R., et al., *Moving sport and exercise science forward: A call for the adoption of more transparent research practices.* Sports Medicine, 2020. **50**(3): p. 449-459. doi: https://doi.org/10.1007/s40279-019-01227-1.

21. Derrick, T.R., et al., *ISB recommendations on the reporting of intersegmental forces and moments during human motion analysis.* Journal of Biomechanics, 2020. **99**: p. 109533. doi: https://doi.org/10.1016/j.jbiomech.2019.109533.

22. Wu, G., et al., *ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - Part I: Ankle, hip, and spine.* Journal of Biomechanics, 2002. **35**(4): p. 543-548. doi: https://doi.org/10.1016/S0021-9290(01)00222-6.

23. Leardini, A., et al., *ISB recommendations for skin-marker-based multi-segment foot kinematics.* Journal of Biomechanics, 2021. **125**: p. 110581. doi: https://doi.org/10.1016/j.jbiomech.2021.110581.

24. Wu, G. and P.R. Cavanagh, *ISB recommendations for standardization in the reporting of kinematic data.* Journal of Biomechanics, 1995. **28**(10): p. 1257-1261. doi: https://doi.org/10.1016/0021-9290(95)00017-c.

25. Wu, G., et al., *ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand.* Journal of Biomechanics, 2005. **38**(5): p. 981-992. doi: https://doi.org/10.1016/j.jbiomech.2004.05.042.

26. Valentine, J.C., et al., *Replication in prevention science.* Prevention Science, 2011. **12**(2): p. 103-17. doi: https://doi.org/10.1007/s11121-011-0217-6.

27. Giakas, G., *Power spectrum analysis and filtering*, in *Nonlinear Analysis for Human Movement Variability*, N. Stergiou, Editor. 2004, Human Kinetics: Champaign, IL. p. 223-258.
28. Wyatt, H.E., et al., *Stable coordination variability in overground walking and running at preferred and fixed speeds.* Journal of Applied Biomechanics, 2021. **37**(4): p. 299-303. doi: https://doi.org/10.1123/jab.2020-0368.
29. Maykut, J.N., et al., *Concurrent validity and reliability of 2d kinematic analysis of frontal plane motion during running.* International Journal of Sports Physical Therapy, 2015. **10**(2): p. 136-46.
30. Sinclair, J., et al., *Three-dimensional kinematic comparison of treadmill and overground running.* Sports Biomechanics, 2013. **12**(3): p. 272-282. doi: https://doi.org/10.1080/14763141.2012.759614.
31. Boyer, K.A. and B.M. Nigg, *Quantification of the input signal for soft tissue vibration during running.* Journal of Biomechanics, 2007. **40**(8): p. 1877-1880. doi: https://doi.org/10.1016/j.jbiomech.2006.08.008.
32. Bartlett, R., *Causes of Movement - Forces and Torques*, in *Introduction to Sports Biomechanics: Analysing Human Movement Patterns*, R. Bartlett, Editor. 2007, Routledge: Abingdon, UK. p. 163-222.
33. Lees, A. and M. Lake, *Force and Pressure Measurement*, in *Biomechanical Evaluation of Movement in Sport and Exercise: The British Association of Sport and Exercise Sciences Guide*, C. Payton and R. Bartlett, Editors. 2007, Routledge: Abingdon, UK. p. 53-76.
34. Day, E.M. and M.E. Hahn, *Does running speed affect the response of joint level mechanics in non-rearfoot strike runners to footwear of varying longitudinal bending stiffness?* Gait & Posture, 2021. **84**: p. 187-191. doi: https://doi.org/10.1016/j.gaitpost.2020.11.029.
35. McDonald, K.A., et al., *Unholey shoes: Experimental considerations when estimating ankle joint complex power during walking and running.* Journal of Biomechanics, 2019. **92**: p. 61-66. doi: https://doi.org/10.1016/j.jbiomech.2019.05.031.
36. Noehren, B., K. Manal, and I. Davis, *Improving between-day kinematic reliability using a marker placement device.* Journal of Orthopaedic Research, 2010. **28**(11): p. 1405-1410. doi: https://doi.org/10.1002/jor.21172.

37. Sinclair, J., et al., *Differences in tibiocalcaneal kinematics measured with skin- and shoe-mounted markers.* Human Movement, 2013. **14**(1): p. 64-69. doi: https://doi.org/10.2478/humo-2013-0005.

38. Bennett, H.J., et al., *A normative database of hip and knee joint biomechanics during dynamic tasks using four functional methods with three functional calibration tasks.* Journal of Biomechanical Engineering, 2020. **142**(4): p. 041011. doi: https://doi.org/10.1115/1.4044503.

39. Hamill, J., G.E. Caldwell, and T.R. Derrick, *Reconstructing digital signals using Shannon's Sampling Theorem.* Journal of Applied Biomechanics, 1997. **13**(2): p. 226-238. doi: https://doi.org/10.1123/jab.13.2.226.

40. Mai, P. and S. Willwacher, *Effects of low-pass filter combinations on lower extremity joint moments in distance running.* Journal of Biomechanics, 2019. **95**: p. 109311. doi: https://doi.org/10.1016/j.jbiomech.2019.08.005.

41. Edwards, W.B., K.L. Troy, and T.R. Derrick, *On the filtering of intersegmental loads during running.* Gait & Posture, 2011. **34**(3): p. 435-438. doi: https://doi.org/10.1016/j.gaitpost.2011.06.006.

42. Schreven, S., P.J. Beek, and J.B. Smeets, *Optimising filtering parameters for a 3D motion analysis system.* Journal of Electromyography and Kinesiology, 2015. **25**(5): p. 808-814. doi: https://doi.org/10.1016/j.jelekin.2015.06.004.

43. Sinclair, J., P.J. Taylor, and S.J. Hobbs, *Digital filtering of three-dimensional lower extremity kinematics: an assessment.* Journal of Human Kinetics, 2013. **39**: p. 25-36. doi: https://doi.org/10.2478/hukin-2013-0065.

44. Hébert-Losier, K., L. Mourot, and H.C. Holmberg, *Elite and amateur orienteers' running biomechanics on three surfaces at three speeds.* Medicine and Science in Sports and Exercise, 2015. **47**(2): p. 381-389. doi: https://doi.org/10.1249/mss.0000000000000413.

45. Sundström, D., M. Kurz, and G. Björklund, *Runners adapt different lower-limb movement patterns with respect to different speeds and downhill slopes.* Frontiers in Sports and Active Living, 2021. **3**: p. 682401. doi: https://doi.org/10.3389/fspor.2021.682401.

46. Stergiou, N., B.T. Bates, and S.L. James, *Asynchrony between subtalar and knee joint function during running.* Medicine and Science in Sports and Exercise, 1999. **31**(11): p. 1645-1655.

47. Skiadopoulos, A. and N. Stergiou, *Power Spectrum and Filtering*, in *Biomechanics and Gait Analysis*, N. Stergiou, Editor. 2020, Elsevier Science: London, UK. p. 99-148.

48. Kristianslund, E., T. Krosshaug, and A.J. van den Bogert, *Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention.* Journal of Biomechanics, 2012. **45**(4): p. 666-71. doi: https://doi.org/10.1016/j.jbiomech.2011.12.011.

49. Bezodis, N.E., A.I. Salo, and G. Trewartha, *Excessive fluctuations in knee joint moments during early stance in sprinting are caused by digital filtering procedures.* Gait & Posture, 2013. **38**(4): p. 653-657. doi: https://doi.org/10.1016/j.gaitpost.2013.02.015.

50. Roewer, B.D., et al., *The 'impact' of force filtering cut-off frequency on the peak knee abduction moment during landing: artefact or 'artifiction'?* British Journal of Sports Medicine, 2014. **48**(6): p. 464-468. doi: https://doi.org/10.1136/bjsports-2012-091398.

51. Giakas, G. and V. Baltzopoulos, *A comparison of automatic filtering techniques applied to biomechanical walking data.* Journal of Biomechanics, 1997. **30**(8): p. 847-850. doi: https://doi.org/10.1016/s0021-9290(97)00042-0.

52. Yu, B., et al., *Estimate of the optimum cutoff frequency for the butterworth low-pass digital filter.* Journal of Applied Biomechanics, 1999. **15**(3): p. 318-329. doi: https://doi.org/10.1123/jab.15.3.318.

53. Myers, S.A., *Time Series*, in *Nonlinear Analysis for Human Movement Variability*, N. Stergiou, Editor. 2018, CRC Press: Boca Raton, FL. p. 29-54.

54. Winter, D.A., *Kinematics*, in *Biomechanics and Motor Control of Human Movement*, D.A. Winter, Editor. 2009, Wiley: Hoboken, NJ. p. 45-81.

55. Ferber, R., et al., *A comparison of within- and between-day reliability of discrete 3D lower extremity variables in runners.* Journal of Orthopaedic Research, 2002. **20**(6): p. 1139-1145. doi: https://doi.org/10.1016/s0736-0266(02)00077-3.

56. Bramah, C., et al., *The between-day repeatability, standard error of measurement and minimal detectable change for discrete kinematic parameters during treadmill running.* Gait & Posture, 2021. **85**: p. 211-216. doi: https://doi.org/10.1016/j.gaitpost.2020.12.032.

57. Bishop, C., G. Paul, and D. Thewlis, *The reliability, accuracy and minimal detectable difference of a multi-segment kinematic model of the foot-shoe complex.* Gait & Posture, 2013. **37**(4): p. 552-557. doi: https://doi.org/10.1016/j.gaitpost.2012.09.020.

58. Kottner, J., et al., *Guidelines for Reporting Reliability and Agreement Studies (GRRAS) were proposed.* Journal of Clinical Epidemiology, 2011. **64**(1): p. 96-106. doi: 10.1016/j.jclinepi.2010.03.002.

59. Lexell, J.E. and D.Y. Downham, *How to assess the reliability of measurements in rehabilitation.* American Journal of Physical Medicine & Rehabilitation, 2005. **84**(9): p. 719-723. doi: https://doi.org/10.1097/01.phm.0000176452.17771.20.

60. Atkinson, G. and A.M. Nevill, *Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine.* Sports Medicine, 1998. **26**(4): p. 217-238. doi: 10.2165/00007256.

61. Hopkins, W.G., et al., *Progressive statistics for studies in sports medicine and exercise science.* Medicine & Science in Sports & Exercise, 2009. **41**(1): p. 3-13. doi: https://doi.org/10.1249/MSS.0b013e31818cb278.

62. Pohl, M.B., C. Lloyd, and R. Ferber, *Can the reliability of three-dimensional running kinematics be improved using functional joint methodology?* Gait & Posture, 2010. **32**(4): p. 559-563. doi: https://doi.org/10.1016/j.gaitpost.2010.07.020.

63. Leardini, A., et al., *Multi-segment foot models and their use in clinical populations.* Gait & Posture, 2019. **69**: p. 50-59. doi: https://doi.org/10.1016/j.gaitpost.2019.01.022.

64. Petit, D.J., J.D. Willson, and J.A. Barrios, *Comparison of stance phase knee joint angles and moments using two different surface marker representations of the proximal shank in walkers and runners.* Journal of Applied Biomechanics, 2014. **30**(1): p. 173-178. doi: https://doi.org/10.1123/jab.2012-0147.

65. Ferrari, A., et al., *Quantitative comparison of five current protocols in gait analysis.* Gait & Posture, 2008. **28**(2): p. 207-216. doi: https://doi.org/10.1016/j.gaitpost.2007.11.009.

66. Collins, T.D., et al., *A six degrees-of-freedom marker set for gait analysis: Repeatability and comparison with a modified Helen Hayes set.* Gait & Posture, 2009. **30**(2): p. 173-180. doi: https://doi.org/10.1016/j.gaitpost.2009.04.004.

67. Miana, A.N., M.V. Prudêncio, and R.M.L. Barros, *Comparison of protocols for walking and running kinematics based on skin surface markers and rigid clusters of*

markers. International Journal of Sports Medicine, 2009. **30**(11): p. 827-833. doi: https://doi.org/10.1055/s-0029-1234054.

68. Pothrat, C., et al., *One- and multi-segment foot models lead to opposite results on ankle joint kinematics during gait: Implications for clinical assessment.* Clinical Biomechanics, 2015. **30**(5): p. 493-499. doi: https://doi.org/10.1016/j.clinbiomech.2015.03.004.

69. Baltzopoulos, V., *Inverse dynamics, joint reaction forces and loading in the musculoskeletal system: guidelines for correct mechanical terms and recommendations for accurate reporting of results.* Sports Biomechanics, 2021: p. 1-14. doi: https://doi.org/10.1080/14763141.2020.1841826.

70. Reinschmidt, C., et al., *Effect of skin movement on the analysis of skeletal knee joint motion during running.* Journal of Biomechanics, 1997. **30**(7): p. 729-32. doi: https://doi.org/10.1016/s0021-9290(97)00001-8.

71. Stacoff, A., et al., *Effects of shoe sole construction on skeletal motion during running.* Medicine and Science in Sports and Exercise, 2001. **33**(2): p. 311-319. doi: https://doi.org/10.1097/00005768-200102000-00022.

72. Reinschmidt, C., et al., *Tibiocalcaneal motion during running, measured with external and bone markers.* Clinical Biomechanics, 1997. **12**(1): p. 8-16. doi: https://doi.org/10.1016/s0268-0033(96)00046-0.

73. Trudeau, M.B., et al., *The calcaneus adducts more than the shoe's heel during running.* Footwear Science, 2017. **9**(2): p. 79-85. doi: https://doi.org/10.1080/19424280.2017.1334712.

74. Alcantara, R.S., M.B. Trudeau, and E.S. Rohr, *Calcaneus range of motion underestimated by markers on running shoe heel.* Gait & Posture, 2018. **63**: p. 68-72. doi: https://doi.org/10.1016/j.gaitpost.2018.04.035.

75. Reinschmidt, C., A. Stacoff, and E. Stüssi, *Heel movement within a court shoe.* Medicine and Science in Sports and Exercise, 1992. **24**(12): p. 1390-1395.

76. Sinclair, J., et al., *Differences in multi-segment foot kinematics measured using skin and shoe mounted markers.* The Foot and Ankle Online Journal, 2014. **7**(2): p. 1-7. doi: https://doi.org/10.3827/faoj.2014.0701.0001.

77. Taylor, W.R., et al., *On the influence of soft tissue coverage in the determination of bone kinematics using skin markers.* Journal of Orthopaedic Research, 2005. **23**(4): p. 726-34. doi: https://doi.org/10.1016/j.orthres.2005.02.006.

78. Butler, R.J., I.S. Davis, and J. Hamill, *Interaction of arch type and footwear on running mechanics.* The American Journal of Sports Medicine, 2006. **34**(12): p. 1998-2005. doi: https://doi.org/10.1177/0363546506290401.

79. Shultz, R. and T. Jenkyn, *Determining the maximum diameter for holes in the shoe without compromising shoe integrity when using a multi-segment foot model.* Medical Engineering & Physics, 2012. **34**(1): p. 118-122. doi: https://doi.org/10.1016/j.medengphy.2011.06.017.

80. Bishop, C., et al., *A method to investigate the effect of shoe-hole size on surface marker movement when describing in-shoe joint kinematics using a multi-segment foot model.* Gait & Posture, 2015. **41**(1): p. 295-299. doi: https://doi.org/10.1016/j.gaitpost.2014.09.002.

81. Mickle, K.J., et al., *Foot pain, plantar pressures, and falls in older people: A prospective study.* Journal of the American Geriatrics Society, 2010. **58**(10): p. 1936-1940. doi: https://doi.org/10.1111/j.1532-5415.2010.03061.x.

82. Redmond, A.C., Y.Z. Crane, and H.B. Menz, *Normative values for the Foot Posture Index.* Journal of Foot and Ankle Research, 2008. **1**(6): p. 1-9. doi: https://doi.org/10.1186/1757-1146-1-6.

83. Tomassoni, D., E. Traini, and F. Amenta, *Gender and age related differences in foot morphology.* Maturitas, 2014. **79**(4): p. 421-427. doi: https://doi.org/10.1016/j.maturitas.2014.07.019.

84. Lussiana, T., et al., *Do subjective assessments of running patterns reflect objective parameters?* European Journal of Sport Science, 2017. **17**(7): p. 847-857. doi: https://doi.org/10.1080/17461391.2017.1325072.

85. Soares, T.S.A., et al., *Acute kinematics changes in marathon runners using different footwear.* Journal of Sports Sciences, 2018. **36**(7): p. 766-770. doi: https://doi.org/10.1080/02640414.2017.1340657.

86. Bishop, C., et al., *A radiological method to determine the accuracy of motion capture marker placement on palpable anatomical landmarks through a shoe.* Footwear Science, 2011. **3**(3): p. 169-177. doi: https://doi.org/10.1080/19424280.2011.635386.