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Measuring biomechanical loads in team sports – from lab to field

Jasper Verheul[1], Niels J. Nedergaard[2], Jos Vanrenterghem[2], Mark A. Robinson[1]

1. Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, United Kingdom
2. Department of Rehabilitation Sciences, KU Leuven, Leuven, Belgium

Corresponding Author:

Jasper Verheul, PhD

Email: J.P.Verheul@ljmu.ac.uk

Address: Tom Reilly Building, Byrom Street, L3 5AF, Liverpool, United Kingdom

ORCID: 0000-0002-2939-8046.

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ABSTRACT

The benefits of differentiating between the physiological and biomechanical load-response pathways in football and other (team) sports have become increasingly recognised. In contrast to physiological loads however, the biomechanical demands of training and competition are still not well understood, primarily due to the difficulty of quantifying biomechanical loads in a field environment. Although musculoskeletal adaptation and injury are known to occur at a tissue level, several biomechanical load metrics are available that quantify loads experienced by the body as a whole, its different structures and the individual tissues that are part of these structures. This paper discusses the distinct aspects and challenges that are associated with measuring biomechanical loads at these different levels in laboratory and/or field contexts. Our hope is that through this paper, sport scientists and practitioners will be able to critically consider the value and limitations of biomechanical load metrics and will keep pursuing new methods to measure these loads within and outside the lab, as a detailed load quantification is essential to better understand the biomechanical load-response pathways that occur in the field.

INTRODUCTION

Optimal sports performance with minimal injury risk is largely determined by the training an athlete has been exposed to. Whilst sufficient training loads are required to achieve beneficial physical adaptations for enhanced performance in the form of improved fitness, excessive loading can introduce fatigue and is known to increase the risk of injury [1,2]. Training loads are, therefore, widely measured and monitored in football and other (team) sports, with the aim to better control training prescription and optimise load-response pathways. On the one hand there is a physiological load-response pathway, where the metabolic challenge to maintain powerful and prolonged skeletal muscle contractions triggers a broad range of biochemical responses in the body, primarily in the form of metabolic and cardiorespiratory adaptations [3,4]. On the other hand, there is a biomechanical load-response pathway, where the mechanical challenges to withstand high forces repetitively applied to the musculoskeletal system triggers mechanobiological tissue responses of the muscles, tendons, ligaments, bones and articular cartilage [5–7]. There is a growing belief that monitoring the physiological and biomechanical loads separately can contribute to the holistic understanding of an athlete's adaptive mechanisms that ultimately determine their physical fitness and performance outcomes [8]. However, in contrast to a considerable understanding of the physiological branch, the extent to which (team) sports imposes loads on the musculoskeletal system and triggers mechanobiological responses that make the tissues stronger or weaker are relatively under-investigated and not well understood.

A major issue that limits the progress in understanding biomechanical load-response pathways, is that measuring *in vivo* biomechanical loads to the musculoskeletal system as a whole, to the various structures within it, and to the tissues making up those structures, remains very difficult or even impossible with the current technologies, especially in a field-based context. Our aim was therefore 1) to provide an overview of biomechanical load metrics at different levels, 2) to discuss current methods and challenges for measuring *in vivo* biomechanical loads, and 3) suggest future considerations and avenues to be explored to enhance field-based biomechanical load monitoring.

TISSUE LOADS

During training and match-play in football and other (team) sports, the different hard- and soft-tissues of the body are exposed to an array of forces. These forces cause mechanical tension within the tissues in the form of stresses and strains that, together with exercise-induced microdamage and metabolic stress, trigger remodelling and repair responses. Examples of such adaptations include alterations in muscle architecture [9,10], changes in tendon stiffness and structure [11–14], and increased bone mass and mineral density [15,16], which are generally considered desirable characteristics for enhanced performance (e.g. higher force production, increased storage and return of elastic energy). Excessive exposure to stresses and strains on the other hand, can outpace repair mechanisms and cause an accumulation of micro-damage that weakens the tissues over time. This progressive weakening can ultimately lead to mechanical fatigue and tissue failure, such as muscle tears, tendon rupture or bone fractures [17,18]. The optimal loading thresholds of individual tissues depend on many factors, including tissue properties and loading history. In an ideal world one would thus want to quantify and monitor the accumulation of tissue-specific stresses and strains over time.

From a mechanical perspective stress and strain can be defined as the force acting per unit surface area and the resulting relative tissue deformation, respectively. This direct relationship between force, stress and strain allows for *in vitro* experiments to be performed to investigate tissue adaptative or failure responses to predefined biomechanical loads [19,20]. Such experiments can provide a detailed insight into tissue behaviour under specific loading conditions, but require highly controlled laboratory setups, homogeneous tissue specimens and strictly constant or repetitive loading patterns. As an alternative, advanced computational modelling approaches (e.g. finite element analysis) can be used to accurately predict stress and strain distributions throughout tissues *in silico*, and investigate their response mechanisms under different mechanical and biological conditions [21,22]. However, there is extensive physiological, structural and morphological variability within musculoskeletal structures, and during sports movements tissues are exposed to highly varying non-uniform tensile, compressive and shear forces. This makes it difficult to translate findings from controlled *in vitro* and/or *in silico* studies to the field, beyond understanding the expected stress-related deformations and stress tolerances of individual tissues. Although biomechanical responses to training loads are thus known to take place at a tissue level, the quantification of tissue-specific loads is primarily restricted to laboratory environments only (Figure 1).

Figure 1 around here

STRUCTURAL LOADS

Much research has investigated loads experienced by the musculoskeletal system at a structural level. Individual organs (e.g. muscles, tendons, ligaments, bones) or a combination thereof (e.g. joints, segments, limbs) form structures on which forces and moments act. These structural loads thus describe the combination of stresses and strains working on the individual tissues comprised by the structure. Net moments about the knee joint structure for example, can be used as an indicator of loading magnitude and injury risk of the anterior cruciate ligament [23,24]. Likewise, measures of joint or leg stiffness, which is the resistance of a structure to withstand the forces acting on it, have been demonstrated to be sensitive to training status [25], running speed [26] and exercise-induced fatigue [27,28] (see [29] for an extensive discussion of the use of stiffness measures in sports). Quantifying structure-specific loading parameters can thus be informative for evaluating the risk of injury or biomechanical adaptations to training.

To indirectly estimate the *in vivo* loads acting on individual structures, including bone and muscle-tendon forces, and joint moments, reaction forces and stiffness parameters, musculoskeletal modelling techniques can be used [30,31]. Although such approaches are traditionally laborious and time consuming, recent advancements have shown the potential for real-time analysis of joint forces and moments, as well as muscle-tendon forces [32–35]. The downside of these methods however, is that they are strongly dependent on kinematic (motion-capture systems), kinetic (force platforms) and/or neuromuscular (electromyography) input, the combination of which is yet largely restricted to laboratories. Several studies have, therefore, aimed to directly measure the *in vivo* structure-specific loads. Surgically implanted force transducers or strain gauges may, for example, be used to measure muscle-tendon forces [36–38] or bone strains [39] for walking, running and jumping activities, but their invasive and temporary nature makes the use of implants unsuitable for large-scale human experiments, let alone day-to-day load monitoring in the field. Very recently, a wearable tensiometer device has shown promising results for non-invasively assessing mechanical properties and loading of superficial tendons [40], and could be a first step towards the direct and field-based measurement of structure-specific loads. The difficulty of directly measuring structural forces has also led to the exploration of various indicators (or surrogate measures) of structural load. Tibial accelerations measured from shank-mounted accelerometers for example, have been suggested to provide a valid, reliable and simple field-based indicator of tibial loading [41–43], but it remains uncertain if tibial accelerations are related to the actual forces, stresses and strains experienced by the bone [44]. In short therefore, despite the availability of several techniques to quantify structural loads directly or indirectly, their application is still primarily bound to a lab context (Figure 1).

WHOLE-BODY LOADS

Besides internal stresses and strains that are experienced by specific tissues and/or structures, the body as a whole is exposed to external forces. These external loads are primarily caused by interactions with other athletes (e.g. during tackling), equipment (e.g. kicking or hitting a ball) or the ground. Ground reaction forces (GRFs) following from foot-ground interactions especially, both drive and are affected by muscular actions, and contribute to impact forces experienced by individual structures. GRFs thus describe the biomechanical loading experienced by the musculoskeletal system as a whole and have been investigated extensively for their potential association with running performance features [45–47] or specific overuse related pathologies [48–50]. Such relationships remain ambiguous though [48,50] and GRF may even be a poor predictor of the loads experienced at a structural level [20,49].

Whilst GRF alone unlikely suffices as a source of information for the prevention or treatment of particular tissue- or structure-specific pathologies, GRF can still provide a generic indicator of cumulative loading of the musculoskeletal system as a whole. In contrast to tissue- and structure-specific loads, GRFs can be measured relatively easily and non-invasively from force platforms. Unfortunately, force platforms are not suitable for sport-specific training and competition environments, and different approaches have been explored to estimate GRF from wearable devices in the field. Probably the most intuitive method is by using instrumented insoles, which are typically worn in or under the shoe and provide a summed measure of the pressure that the foot exerts on the ground [51]. Although pressure insoles can estimate GRF for running and jumping fairly well [52–56], their compromised accuracy for high-intensity movements [52,54–56] and practical limitations (e.g. movement restrictions, added mass in the shoe, discomfort) [51], leaves the feasibility of using insoles for monitoring GRF on a large-scale in the field currently still questionable.

Based on the relationship between force and acceleration according to Newton's second law ($F=m\cdot a$), segmental movements may be used to indirectly estimate GRF [57–59]. Currently popular body-worn accelerometers have, therefore, received special attention for their potential to measure GRF in this manner [41,60–65]. Several studies have, however, demonstrated that either whole GRF waveforms [60–62], or even specific GRF features [41,61,63], cannot be estimated well from individual trunk-, pelvis- or shank-mounted accelerometers. In fact, the majority of segmental accelerations are likely required to accurately estimate GRF [57,58], making the use of one or even a combination of several accelerometer units to predict GRF probably insufficient.

Besides GRF, other accelerometry-based metrics have been suggested to assess whole-body loading, including vertical stiffness [66–68] and cumulative acceleration metrics [69–74]. Vertical stiffness is assumed to represent the whole-body response to the dynamic external forces and may be used to assess neuromuscular fatigue and performance after different types of training [67,68]. Likewise, cumulative acceleration metrics (e.g. PlayerLoad^{TM}, New Body Load, Dynamic Stress Load, Force Load [69–74]) are thought to provide an indication of the accumulated external impacts the body is exposed to. However, the premise underpinning these metrics that accelerations of individual segments appropriately represent the whole-body acceleration is probably not valid [60], while evidence for a relationship with loads acting on a structural or tissue level is yet lacking. As such, if associations between any of these metrics and performance improvements or increased injury risk are observed, this does not provide an explanation for the underlying mechanisms of such associations. In other words, although GRF, stiffness or accelerometry-derived metrics offer field-based methods to quantify whole-body loading (Figure 1), their relevance and intrinsic value for assessing load-response pathways at a structural or tissue level remains to be determined.

FROM LAB TO FIELD

A big hurdle for translating research into the biomechanical load-response pathways from the lab to the field is the difficulty of quantifying biomechanical loads. This is primarily due to the lack of means to accurately measure biomechanical information in an athlete's natural training and/or competition environment (e.g. a football pitch). Recent developments have, however, demonstrated that such information might become more easily available in applied sport settings in the near future. For example, full-body wireless inertial sensor suits have been shown to be a reliable and valid method to simultaneously measure kinematic information of all body segments outside the laboratory (e.g. Xsens MVN [75]), and can already provide GRF and joint moment estimates during stereotypical activities such as walking [76,77]. To overcome discomfort and movement restriction issues associated with the use of multiple body-worn devices, markerless motion capture techniques are a non-invasive method for measuring different biomechanical variables in various sport environments [78–83]. These techniques may in the future allow for load metrics to be estimated at different levels. If for example, information from body-worn sensors or markerless motion capture can be used to accurately estimate GRF [58,84], the combination of kinematics and GRF may eventually be used to estimate structure-specific loading and thus open the door to field-based measurements and monitoring of internal biomechanical loads.

Given the often-limited availability of information in day-to-day football environments (as well as other applied sports settings), estimating biomechanical loads using conventional mechanical methods that attempt to directly measure load is not always possible. An imminent area in sports biomechanics that overcomes this issue is the use of advanced machine learning approaches to identify and/or predict biomechanical variables of interest [85]. For example, neural network methods have been used to predict GRF and moments [86,87] and joint forces [88] from body-worn inertial sensors for different running tasks. Although these studies show promising results, interpreting the underlying biomechanical mechanisms of the predicted variable can be difficult [85,89], which could limit their application for e.g. explaining adaptation criteria or injury mechanisms. If similar techniques can be used to accurately predict tissue- or structure-specific forces however, this may enable large-scale and non-invasive internal load monitoring in the field.

To effectively investigate and describe biomechanical load-response pathways in the field, the relevance of metrics used to quantify loads acting on the musculoskeletal system, as well as the outcome measures against which these loads are validated, should be considered. Popular body-worn sensor technologies especially, have opened the door for relatively easy measurements of several indicators of whole-body loading, but the applied researcher or practitioner should be reminded that their relationship with established tissue or structural load metrics, or their relevance in the context of the adaptive or injury mechanisms, has not been validated. For example, changes observed at a whole-body level (e.g. technique changes in a fatigued state) can be insightful when assessing generic whole-body adaptations to training but as yet, cannot be used to directly infer on load-response pathways experienced by individual tissues or structures. Therefore, careful validation is required for such field-based metrics against measures of tissue and/or structural responses (e.g. from tissue biopsies or ultrasound scanning) to establish the relationships between available biomechanical load metrics and the adaptive or injury mechanisms occurring at internal levels.

CONCLUSION

Biomechanical load-response pathways can be explained at different levels of the musculoskeletal system. Due to the currently limited availability of field-based biomechanical load metrics, enhancing our understanding of what biomechanical load metrics can and cannot be used for is essential. Our hope is that through this paper, sport scientists and practitioners alike will revisit their views on the value and limitations of biomechanical load metrics at different levels. Moreover, we would like to encourage sport scientists and biomechanics researchers to keep pursuing ways to overcome the challenges of measuring these loads within and outside the lab, as a detailed quantification of biomechanical loads experienced during football and other (team) sports is essential to further understand the *in vivo* biomechanical load-response pathways and ultimately monitor them in the field.

REFERENCES

1 Eckard TG, Padua DA, Hearn DW, *et al. The Relationship Between Training Load and Injury in Athletes: A Systematic Review*. Springer International Publishing 2018. doi:10.1007/s40279-018-0951-z

2 Drew MK, Finch CF. The Relationship Between Training Load and Injury, Illness and Soreness: A Systematic and Literature Review. *Sport Med* Published Online First: 2016. doi:10.1007/s40279-015-0459-8

3 Impellizzeri FM, Rampinini E, Marcora SM. Physiological assessment of aerobic training in soccer. *J Sports Sci* 2005;**23**:583–92. doi:10.1080/02640410400021278

4 MacInnis MJ, Gibala MJ. Physiological adaptations to interval training and the role of exercise intensity. *J Physiol* 2017;**595**:2915–30. doi:10.1113/JP273196

5 Rosa N, Simoes R, Magalhães FD, *et al.* From mechanical stimulus to bone formation: A review. *Med Eng Phys* 2015;**37**:719–28. doi:10.1016/j.medengphy.2015.05.015

6 Bohm S, Mersmann F, Arampatzis A. Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults. *Sport Med - Open* 2015;**1**:7. doi:10.1186/s40798-015-0009-9

7 Wisdom KM, Delp SL, Kuhl E. Use it or lose it: multiscale skeletal muscle adaptation to mechanical stimuli. *Biomech Model Mechanobiol* 2015;**14**:195–215. doi:10.1007/s10237-014-0607-3

8 Vanrenterghem J, Nedergaard NJ, Robinson MA, *et al.* Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways. *Sport Med* 2017;**47**:2135–42. doi:10.1007/s40279-017-0714-2

9 Nimphius S, McGuigan MR, Newton RU. Changes in Muscle Architecture and Performance During a Competitive Season in Female Softball Players. *J Strength Cond Res* 2012;**26**:2655–66.

10 Secomb JL, Farley OR, Nimphius S, *et al.* The training-specific adaptations resulting from resistance training, gymnastics and plyometric training, and non-training in adolescent athletes. *Sport Sci Coach* 2017;**12**:762–73. doi:10.1177/1747954117727810

11 Couppe C, Kongsgaard M, Aagaard P, *et al.* Habitual loading results in tendon hypertrophy and increased stiffness of the human patellar tendon. *J Appl Physiol* 2008;**105**:805–10.

doi:10.1152/japplphysiol.90361.2008

12 Mersmann F, Bohm S, Schroll A, *et al.* Muscle and tendon adaptation in adolescent athletes: A longitudinal study. *Scand J Med Sci Sports* 2017;**27**:75–82. doi:10.1111/sms.12631

13 Esmaeili A, Stewart AM, Hopkins WG, *et al.* Effects of Training Load and Leg Dominance on Achilles and Patellar Tendon Structure. *Int J Sports Physiol Perform* 2017;**12**:S2-122-S2-126.

14 Rabello LM, Zwerver J, Stewart RE, *et al.* Patellar tendon structure responds to load over a 7 - week preseason in elite male volleyball players. *Scand J Med Sci Sports* 2019;:1–8. doi:10.1111/sms.13428

15 Fredericson M, Chew K, Ngo J, *et al.* Regional bone mineral density in male athletes: a comparison of soccer players, runners and controls. *Br J Sports Med* 2007;**41**:664–8. doi:10.1136/bjsm.2006.030783

16 Helge EW, Andersen T., Schmidt JF, *et al.* Recreational football improves bone mineral density and bone turnover marker profile in elderly men. *Scand J Med Sci Sports* 2014;**24**:98–104. doi:10.1111/sms.12239

17 Edwards WB. Modeling Overuse Injuries in Sport as a Mechanical Fatigue Phenomenon. *Exerc Sport Sci Rev* 2018;**46**:224–31. doi:10.1249/JES.0000000000000163

18 Bertelsen ML, Hulme A, Petersen J, *et al.* A framework for the etiology of running-related injuries. *Scand J Med Sci Sport* 2017;**27**:1170–80. doi:10.1111/sms.12883

19 Wang T, Lin Z, Day RE, *et al.* Programmable mechanical stimulation influences tendon homeostasis in a bioreactor system. *Biotechnol Bioeng* 2013;**110**:1495–507. doi:10.1002/bit.24809

20 Loundagin LL, Schmidt TA, Edwards WB. Mechanical Fatigue of Bovine Cortical Bone Using Ground Reaction Force Waveforms in Running. *J Biomech Eng* 2018;**140**. doi:10.1115/1.4038288

21 Amirouche F, Bobko A. Bone Remodeling and Biomechanical Processes- A Multiphysics Approach. *Austin J Biotechnol Bioeng* 2015;**2**:id1041.

22 Smith DW, Rubenson J, Lloyd D, *et al.* A conceptual framework for computational models of Achilles tendon homeostasis. *WIREs Syst Biol Med* 2013;**5**:523–38. doi:10.1002/wsbm.1229

23 Hewett TE, Myer GD, Ford KR, *et al.* Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective

Study. *Am J Sports Med* 2005;**33**:492–501.

24 Lin C, Liu H, Gros MT, *et al.* Biomechanical risk factors of non-contact ACL injuries: A stochastic biomechanical modeling study. *J Sport Heal Sci* 2012;**1**:36–42. doi:10.1016/j.jshs.2012.01.001

25 Verheul J, Clansey AC, Lake MJ. Adjustments with running speed reveal neuromuscular adaptations during landing associated with high mileage running training. *J Appl Physiol* 2017;**122**:653–665. doi:10.1152/japplphysiol.00801.2016

26 Arampatzis A, Brüggemann G-P, Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. *J Biomech* 1999;**32**:1349–53.

27 Morin JB, Samozino P, Millet GY. Changes in running kinematics, kinetics, and spring-mass behavior over a 24-h run. *Med Sci Sports Exerc* 2011;**43**:829–36. doi:10.1249/MSS.0b013e3181fec518

28 Oliver JL, De Ste MBA, Lloyd RS, *et al.* Altered neuromuscular control of leg stiffness following soccer-specific exercise. *Eur J Appl Physiol* 2014;**114**:2241–9. doi:10.1007/s00421-014-2949-z

29 Maloney SJ, Fletcher IM. Lower limb stiffness testing in athletic performance: a critical review. *Sport Biomech* 2018;**3141**:1–22. doi:10.1080/14763141.2018.1460395

30 Seth A, Hicks JL, Uchida TK, *et al.* OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement. *PLoS Comput Biol* 2018;**14**:e1006223. doi:10.1371/journal.pcbi.1006223

31 Scott SH, Winter DA. Internal forces at chronic running injury sites. *Med Sci Sports Exerc* 1990;**22**:357–69.

32 Pizzolato C, Saxby DJ, Ceseracciu E, *et al.* Biofeedback for gait retraining based on real-time estimation of tibiofemoral joint contact forces. *Trans Neural Syst Rehabil Eng* 2017;**25**:1612–21.

33 Pizzolato C, Reggiani M, Modenese L, *et al.* Real-time inverse kinematics and inverse dynamics for lower limb applications using OpenSim. *Comput Methods Biomech Biomed Engin* 2017;**20**:436–45. doi:10.1080/10255842.2016.1240789

34 van den Bogert AJ, Geijtenbeek T, Even-Zohar O, *et al.* A real-time system for biomechanical analysis of human movement and muscle function. *Med Biol Eng Comput* 2013;**51**:1069–77. doi:10.1007/s11517-013-1076-z

35 Manal K, Gravare-Silbernagel K, Buchanan TS. A real-time EMG-driven musculoskeletal model of the ankle. *Multibody Syst Dyn* 2012;**28**:169–80. doi:10.1007/s11044-011-9285-4

36 Fukashiro S, Komi P V., Järvinen M, *et al.* In vivo achilles tendon loading' during jumping in humans. *Eur J Appl Physiol Occup Physiol* 1995;**71**:453–458.

37 Komi P V., Salonen M, Järvinen M, *et al.* In Vivo Registration of Achilles Tendon Forces in Man. I. Methodological Development. *Int J Sport Med* 1987;**8**:3–8.

38 Komi P V. Relevance of in vivo force measurements to human biomechanics. *J Biomech* 1990;**23**:23–34. doi:10.1016/0021-9290(90)90038-5

39 Burr DB, Milgrom C, Fyhrie D, *et al.* In Vivo Measurement of Human Tibial Strains During Vigorous Activity. *Bone* 1996;**18**:405–10.

40 Martin JA, Brandon SCE, Keuler EM, *et al.* Gauging force by tapping tendons. *Nat Commun* 2018;**9**:1–9. doi:10.1038/s41467-018-03797-6

41 Raper DP, Witchalls J, Philips EJ, *et al.* Use of a tibial accelerometer to measure ground reaction force in running: A reliability and validity comparison with force plates. *J Sci Med Sport* 2018;**21**:84–8. doi:10.1016/j.jsams.2017.06.010

42 Milner CE, Ferber R, Pollard CD, *et al.* Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc* 2006;**38**:323–8. doi:10.1249/01.mss.0000183477.75808.92

43 Hennig EM, Lafortune MA. Relationships between ground reaction force and tibial bone acceleration parameters. *Int J Sport Biomech* 1991;**7**:303–9.

44 Sheerin KR, Reid D, Besier TF. The measurement of tibial acceleration in runners. A review of the factors that can affect tibial acceleration during running and evidence based guidelines for its use. *Gait Posture* 2019;**67**:12–24. doi:10.1016/j.gaitpost.2018.09.017

45 Nagahara R, Mizutani M, Matsuo A, *et al.* Association of sprint performance with ground reaction forces during acceleration and maximal speed phases in a single sprint. *J Appl Biomech* 2017;:1–20. doi:10.1123/jab.2016-0356

46 Bezodis NE, North JS, Razavet JL. Alterations to the orientation of the ground reaction force vector affect sprint acceleration performance in team sports athletes. *J Sports Sci* 2017;**35**:1817–24.

doi:10.1080/02640414.2016.1239024

47 Rabita G, Dorel S, Slawinski J, *et al.* Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion. *Scand J Med Sci Sports* 2015;**25**:583–94. doi:10.1111/sms.12389

48 Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. *Clin Biomech* 2011;**26**:23–8. doi:10.1016/j.clinbiomech.2010.08.005

49 Matijevich ES, Branscombe LM, Scott LR, *et al.* Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. *PLoS One* 2019;**14**:e0210000. doi:10.1371/journal.pone.0210000

50 van der Worp H, Vrielink JW, Bredeweg SW. Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis. *Br J Sports Med* 2016;**50**:450–7. doi:10.1136/bjsports-2015-094924

51 Ramirez-Bautista JA, Huerta-Ruelas JA, Chaparro-Cárdenas SL, *et al.* A Review in Detection and Monitoring Gait Disorders Using In-Shoe Plantar Measurement Systems. *IEEE Rev Biomed Eng* 2017;**10**:299–309. doi:10.1109/RBME.2017.2747402

52 Renner KE, Williams DSB, Queen RM. The Reliability and Validity of the Loadsol® under Various Walking and Running Conditions. *Sensors* 2019;**19**:1–14. doi:10.3390/s19020265

53 Burns GT, Zendler JD, Zernicke RF. Validation of a wireless shoe insole for ground reaction force measurement. *J Sports Sci* 2018;:1–10. doi:10.1080/02640414.2018.1545515

54 Seiberl W, Jensen E, Merker J, *et al.* Accuracy and precision of loadsol® insole force- sensors for the quantification of ground reaction force-based biomechanical running parameters parameters. *Eur J Sport Sci* 2018;**18**:1100–9. doi:10.1080/17461391.2018.1477993

55 Park J, Na Y, Gu G, *et al.* Flexible insole ground reaction force measurement shoes for jumping and running. *Proc IEEE RAS EMBS Int Conf Biomed Robot Biomechatronics* 2016;**2016-July**:1062–7. doi:10.1109/BIOROB.2016.7523772

56 Peebles AT, Maguire LA, Renner KE, *et al.* Validity and Repeatability of Single-Sensor Loadsol Insoles during Landing. *Sensors* 2018;**18**:1–10. doi:10.3390/s18124082

57 Pavei G, Seminati E, Cazzola D, *et al.* On the estimation accuracy of the 3D body center of mass trajectory during human locomotion: Inverse vs. forward dynamics. *Front Physiol* 2017;**8**:1–13. doi:10.3389/fphys.2017.00129

58 Verheul J, Gregson W, Lisboa PJ, *et al.* Whole-body biomechanical load in running-based sports: The validity of estimating ground reaction forces from segmental accelerations. *J Sci Med Sport* 2019;**22**:716–22. doi:10.1016/j.jsams.2018.12.007

59 Bobbert MF, Schamhardt HC, Nigg BM. Calculation of vertical ground reaction force estimates during running from positional data. *J Biomech* 1991;**24**:1095–105. doi:10.1016/0021-9290(91)90002-5

60 Nedergaard NJ, Robinson MA, Eusterwiemann E, *et al.* The Relationship Between Whole-Body External Loading and Body-Worn Accelerometry During Team-Sport Movements. *Int J Sports Physiol Perform* 2017;**12**:18–26.https://search.ebscohost.com/login.aspx?direct=true&db=sph&AN=121191349&site=ehost-live

61 Edwards S, White S, Humphreys S, *et al.* Caution using data from triaxial accelerometers housed in player tracking units during running. *J Sports Sci* 2019;**37**:810–8. doi:10.1080/02640414.2018.1527675

62 Nedergaard NJ, Verheul J, Drust B, *et al.* The feasibility of predicting ground reaction forces during running from a trunk accelerometry driven mass-spring-damper model. *PeerJ* 2018;**6**:e6105. doi:10.7717/peerj.6105

63 Wundersitz DWT, Netto KJ, Aisbett B, *et al.* Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running and change-of-direction tasks. *Sport Biomech* 2013;**12**:403–12. doi:10.1080/14763141.2013.811284

64 Gurchiek RD, McGinnis RS, Needle AR, *et al.* The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks. *J Biomech* 2017;**61**:263–8. doi:10.1016/j.jbiomech.2017.07.035

65 Neugebauer JM, Collins KH, Hawkins DA. Ground Reaction Force Estimates from ActiGraph GT3X+ Hip Accelerations. *PLoS One* 2014;**9**:e99023. doi:10.1371/journal.pone.0099023

66 Gaudino P, Gaudino C, Alberti G, *et al.* Biomechanics and predicted energetics of sprinting on sand: Hints for soccer training. *J Sci Med Sport* 2013;**16**:271–5. doi:10.1016/j.jsams.2012.07.003

67 Buchheit M, Gray A, Morin J-B. Assessing stride variables and vertical stiffness with GPS-embedded accelerometers: preliminary insights for the monitoring of neuromuscular fatigue on the field. *J Sport Sci Med* 2015;:698–701.

68 Buchheit M, Lacome M, Cholley Y, *et al.* Neuromuscular Responses to Conditioned Soccer Sessions Assessed via GPS-Embedded Accelerometers: Insights Into Tactical Periodization. *Int J Sports Physiol Perform* 2018;**13**:577–83.

69 Page RM, Marrin K, Brogden CM, *et al.* Biomechanical and physiological response to a contemporary soccer match-play simulation. *J Strength Cond Res* 2015;**29**:2860–6.

70 Colby MJ, Dawson B, Heasman J, *et al.* Accelerometer and GPS-Derived Running Loads and Injury Risk in Elite Australian Footballers. *J Strength Cond Res* 2014;**28**:2244–52.

71 Barrett S, Midgley A, Lovell R. PlayerLoad^{TM}: Reliability, convergent validity, and influence of unit position during treadmill running. *Int J Sports Physiol Perform* 2014;**9**:945–52. doi:10.1123/ijspp.2013-0418

72 Gaudino P, Alberti G, Iaia FM. Estimated metabolic and mechanical demands during different small-sided games in elite soccer players. *Hum Mov Sci* 2014;**36**:123–33. doi:10.1016/j.humov.2014.05.006

73 Ehrmann FE, Duncan CS, Sindhusake D, *et al.* GPS and Injury Prevention in Professional Soccer. *J Strength Cond Res* 2016;**30**:360–7.

74 Boyd LJ, Ball K, Aughey RJ. The reliability of minimaxX accelerometers for measuring physical activity in australian football. *Int J Sports Physiol Perform* 2011;**6**:311–21.

75 Roetenberg D, Luinge H, Slycke P. Xsens MVN: Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors. 2013. doi:10.1.1.569.9604

76 Karatsidis A, Bellusci G, Schepers MH, *et al.* Estimation of Ground Reaction Forces and Moments During Gait Using Only Inertial Motion Capture. *Sensors* 2017;**17**:1–22. doi:10.3390/s17010075

77 Konrath J, Karatsidis A, Schepers MH, *et al.* Estimation of the Knee Adduction Moment and Joint Contact Force during Daily Living Activities Using Inertial Motion Capture. *Sensors* 2019;**19**:1–12. doi:10.3390/s19071681

78 Corazza S, Mündermann L, Chaudhari AM, *et al.* A markerless motion capture system to study

musculoskeletal biomechanics: Visual hull and simulated annealing approach. *Ann Biomed Eng* 2006;**34**:1019–29. doi:10.1007/s10439-006-9122-8

79 Abrams GD, Harris AHS, Andriacchi TP, *et al.* Biomechanical analysis of three tennis serve types using a markerless system. *Br J Sports Med* 2014;**48**:339–42. doi:10.1136/bjsports-2012-091371

80 Fung SK, Sundaraj K, Ahamed NU, *et al.* Hybrid markerless tracking of complex articulated motion in golf swings. *J Bodyw Mov Ther* 2014;**18**:220–7. doi:10.1016/j.jbmt.2013.05.011

81 Grigg J, Haakonssen E, Rathbone E, *et al.* The validity and intra-tester reliability of markerless motion capture to analyse kinematics of the BMX Supercross gate start. *Sport Biomech* 2018;**17**:383–401. doi:10.1080/14763141.2017.1353129

82 Saylor K, Nicolella D, Chambers D, *et al.* Markerless biomechanics analysis for optimization of soldier physical performance. *J Sci Med Sport* 2017;**20S**:S119. doi:10.1016/j.jsams.2017.09.431

83 Perrott MA, Pizzari T, Cook J, *et al.* Comparison of lower limb and trunk kinematics between markerless and marker-based motion capture systems. *Gait Posture* 2017;**52**:57–61. doi:10.1016/j.gaitpost.2016.10.020

84 Skals S, Jung MK, Damsgaard M, *et al.* Prediction of ground reaction forces and moments during sports-related movements. *Multibody Syst Dyn* 2017;**39**:175–95. doi:10.1007/s11044-016-9537-4

85 Halilaj E, Rajagopal A, Fiterau M, *et al.* Machine Learning in Human Movement Biomechanics: Best Practices, Common Pitfalls, and New Opportunities. *J Biomech* Published Online First: 2018. doi:10.1016/j.jbiomech.2018.09.009

86 Wouda FJ, Giuberti M, Bellusci G, *et al.* Estimation of Vertical Ground Reaction Forces and Sagittal Knee Kinematics During Running Using Three Inertial Sensors. *Front Physiol* 2018;**9**:1–14. doi:10.3389/fphys.2018.00218

87 Johnson WR, Mian A, Robinson MA, *et al.* Multidimensional ground reaction forces and moments from wearable sensor accelerations via deep learning. *arXiv Prepr* 2019.

88 Stetter BJ, Ringhof S, Krafft FC, *et al.* Estimation of Knee Joint Forces in Sport Movements Using Wearable Sensors and Machine Learning. *Sensors* 2019;**19**:3690. doi:10.3390/s19173690

89 Doshi-Velez F, Kim B. Towards A Rigorous Science of Interpretable Machine Learning. *ArXiv Prepr*

2017;**1702.08608**.http://arxiv.org/abs/1702.08608

FIGURE CAPTIONS

Figure 1 Schematic overview of currently available biomechanical load metrics. The feasibility of measuring these metrics, ranging from strictly limited to the laboratory to viable in field environments, is indicated along the y-axis. The level at which loads act on the musculoskeletal system is indicated along the x-axis. The different hard- and soft-tissues affected by each load metric are shown in red (muscles), green (tendons and ligaments) and/or blue (bones and cartilage). Metrics to assess tissue- or structure-specific loads that are viable to be measured in the field are still lacking.