Estimating Bone Loading during Physical Activity: Where Do We Go next?

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Abstract: Bone stress injuries affect athletic populations who undertake activities in which bones are repeatedly loaded. In order to understand and reduce the risk of bone stress injuries, we need to quantify the loading experienced by the bones during activities such as running. Bone loading is difficult to quantify as the magnitudes of stress are influenced to a large extent by the magnitude of muscular forces acting on the bone. Musculoskeletal modelling, ranging from very simple to very complex approaches, can be used to estimate the internal loading experienced by the bone during human movement such as running. This has allowed us to explore factors such as speed, slope, step width and step length and their influence on bone loading during running. However, in order to truly understand risk of stress injuries this needs to be taken out of the lab and in-field. Today we have access to rapidly improving technology and data processing capabilities. Could this facilitate the estimation of bone loading in real time? What are the current limitations and challenges, and how might these be overcome in the future?

1 BACKGROUND

Running is one of the most accessible and popular forms of physical activity worldwide, yet healthy people who run are at a high risk of injury, particularly to the lower limbs (van Gent et al., 2007). Bone stress injuries are problematic as they result in several months of time loss. Stress fractures are the most severe stress injury, and comprise up to 30% of running-related injuries (Robertson & Wood, 2017). The tibia is the most common site of stress injury (Wood et al., 2014), followed by the second and third metatarsals (Bennell et al., 1996; Fetzer & Wright, 2006; Gross & Bunch, 1989; Iwamoto & Takeda, 2003).

Bone stress injuries affect athletic populations who undertake activities in which bones are repeatedly loaded. During running, the bone is typically loaded to stress magnitudes considerably below the failure threshold (Burr et al., 1996; Milgrom et al., 2000), however the repetitive nature of the loading can result in risk of injury (Burr et al., 1997; Warden et al., 2014) due to microdamage accumulation. Excessive accumulation of microdamage without sufficient recovery can lead to increased risk of stress fractures (Burr, 2011).

During weight-bearing activities such as running, the bone is subjected to external forces and muscular forces, which contribute to both axial and bending loading of the bone. Typically, the net external forces bend the bone in one direction, whilst the net muscular forces tend to counteract these and act in the opposite direction (Pauwels, 1980). The bending moments acting on the bone result in compression on one surface of the bone and tension on the opposite surface, and this tends to result in tension on the anterior surface of the tibia (Derrick et al., 2016; Meardon et al., 2015; Meardon & Derrick, 2014; H. Rice et al., 2019) and the plantar surface of the metatarsals (Arndt et al., 2002; Ellison, Kenny, et al., 2020) during the majority of the stance phase of running. The magnitude of compression is greater overall than the magnitude of tension on the opposite side, as the stress due to the bending is superimposed with the stress due to longitudinal compression.

In order to understand and reduce the risk of bone stress injuries, we need to be able to quantify the loading experienced by the bones during activities such as running. Bone loading is difficult to quantify, as the magnitudes of stress are influenced to a large extent by the magnitude of muscular forces acting on the bone which cannot be directly measured. Existing estimates of internal bone loading have included

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invasive direct measurement approaches (Arndt et al., 1999, 2002; Burr et al., 1996; Milgrom et al., 2000) using strain gauges. Modelling approaches have been increasingly used to address such research questions, with varying degrees of complexity (Ellison, Akrami, et al., 2020; Ellison, Kenny, et al., 2020; Firminger et al., 2017; Gross & Bunch, 1989; H. Rice et al., 2019; H. M. Rice et al., 2020; Stokes et al., 1979). These approaches have allowed us to explore factors such as speed, slope, step width and step length and their influence on bone loading during running (Baggaley et al., 2021; Edwards et al., 2009, 2010; Meardon et al., 2015). Such understanding is valuable in helping athletes and recreational runners to adapt their training in order to minimise risk of a bone stress injury, but current understanding is limited in two key ways: 1) these approaches need to be taken out of the lab and into the field; 2) the modelling approaches require further evaluation and ultimately validation. In addition, few findings have been replicated or supported in similar populations, and this is essential for scientific integrity.

2 IN-FIELD ASSESSMENT

Modern wearable devices can be worn in-field during physical activity to collect data, including kinematic and kinetic data. Recent advances in wearable devices have made in-field data collection more accessible (Willy, 2018). Examples of such devices include wrist- or ankle-worn accelerometers and gyroscopes, pressure-sensing insoles, and electromyography electrodes. The potential benefits of this are clear, but researchers should be careful not to infer injury causation from single external loading variables as these may not be representative of *internal loading* (Ellison et al., 2021; Ellison, Kenny, et al., 2020; Matijevich et al., 2019). For example, according to subject-specific musculoskeletal models, greater external forces under the metatarsals during running do not simply translate to proportionally greater internal peak stresses (Ellison, Kenny, et al., 2020). However, there is the potential to use combined information from multiple wearable devices to estimate internal loading, through machine learning. Matijevich et al. (Matijevich et al., 2020) demonstrated that multi-sensor algorithms can improve estimates of musculoskeletal loads, such as tibial forces, compared with existing approaches.

In order to quantify internal bone loading in-field using modelling approaches, we must be able to measure the necessary input variables with the required accuracy. The input variables required for the model are dependent upon the complexity of the model. The ‘correct’ level of complexity is therefore the simplest model that can provide valid answers to the specific research question being addressed. Bone geometry is understood to be an important contributor to bone stress magnitude (Ellison, Kenny, et al., 2020) and to risk of stress injury (Nunns et al., 2016) yet their input into musculoskeletal models can add considerable financial and computational expense, due to the requirement for magnetic resonance images or computer tomographic scans if density is also to be considered. Whether sufficiently valid estimates of bone loading can be obtained using generic scaled geometry warrants further investigation. It is likely that such modelling approaches could provide more robust estimates of within-person change in bone stress magnitude (for example in two different footwear conditions) than between-participant differences (for example identifying runners who display higher stress than average).

Whilst information about participant-specific bone geometry and density are difficult to obtain, they do not need to be collected in real-time and therefore do not limit the possibility of accurately estimating bone loading in real-time. The real-time inputs into the model include kinematic and kinetic data during the stance phase of running, which can be estimated using wearable devices with almost instantaneous feedback. One of the greatest challenges with musculoskeletal modelling of bone loading in real-time is estimating muscular forces, often done using static optimization constrained to joint moments (Baggaley et al., 2021; Derrick et al., 2016; Edwards et al., 2010; Meardon & Derrick, 2014; H. Rice et al., 2019). This requires non-negligible computation time and relies on accurate joint moment estimates, two aspects which challenge the ability to quantify bone loading in real-time during running.

In order for the potential advances in estimating bone loading in-field to be realised, technology must be sufficiently robust and accurate for the research question. For example, when considering running in-field, there is a need for wearable technologies that have longevity (e.g. over the course of a training intervention), sufficient battery life and resistance to different weather conditions, amongst other practical considerations.

3 VALIDATION OF MODELLING APPROACHES

Validation of musculoskeletal modelling is another of the greatest challenges and limitations in this field. There is not a clear ‘gold standard’ measurement approach to validate against, as the *in vivo* measurements have considerable limitations of their own. Currently, many approaches are evaluated by comparison with existing approaches, providing convergent validity but no direct validation. More robust validation is essential to advance the field. A first step towards achieving this would be to obtain baseline data from participants during running, such that the bone stresses could be estimated using a variety of approaches with a range of complexity. These participants would then be followed up over time to quantify changes in markers of bone stress reactions or injury outcomes. With sufficient statistical power, it would then be possible to quantify the ability of each modelling approach to predict bone stress outcomes. Furthermore, the simplest model that can be used to achieve a reasonable prediction of bone stress outcomes could be identified, allowing this approach to be developed to provide real-time feedback.

4 TECHNOLOGY AND THE FUTURE

Since running is such an accessible form of physical activity that is popular worldwide, it can play an important role in maintaining physical activity levels throughout the lifespan. In today’s ageing society it is particularly crucial that adults can maintain healthy physical activity levels whilst minimising the risk of stress-related injuries. Not only is the burden of lower limb stress injuries well-documented in adults who run, stress injuries also present a major problem in military populations (Beck, 1998; Knapik et al., 2004; Milgrom et al., 1985; Orr et al., 2014), in adolescent athletes (Field et al., 2011) and in postmenopausal women (Pegrum et al., 2012).

The possibility of quantifying tissue loading in real-time using wearable devices can be exploited by wearable device manufacturers for the benefit of many users. For example, apps for use with mobile devices could be developed that would collect synchronised data from wearable devices worn by the user and estimate bone stresses in real-time. These apps could record cumulative internal loading in each training session, as well as providing real-time feedback - for example via an audible signal - when certain thresholds are exceeded. This has the potential to transform how people structure and plan their running, whether they run for healthy physical activity, to train for competitions, or as part of military training. Ultimately, this could result in reduced stress injury occurrence. Similarly, there is potential for footwear manufacturers to develop footwear that reduces internal loading on structures and therefore injury risk.

There is increasing acknowledgement that the existing approach of inferring injury risk from a single externally-measured variable can result in misleading recommendations. By combining the ability to estimate internal loading using wearable devices in-field with an improved understanding of how this translates to tissue loading, there is the potential for important societal impact.

5 CONCLUSION

There is enormous potential for bone loading to be quantified in real-time, in-field, in the near future. This has important implications and potential to reduce the risk of overuse bone stress injuries, but it is important that the understanding is not outpaced by the development of technology. We must improve our understanding of the validity of the measures as they are taken into the field.

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