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Mechanical misconceptions: Have we lost the "mechanics" in "sports biomechanics"?

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ABSTRACT

Biomechanics principally stems from two disciplines, mechanics and biology. However, both the application and language of the mechanical constructs are not always adhered to when applied to biological systems, which can lead to errors and misunderstandings within the scientific literature. Here we address three topics that seem to be common points of confusion and misconception, with a specific focus on sports biomechanics applications: (1) joint reaction forces as they pertain to loads actually experienced by biological joints; (2) the partitioning of scalar quantities into directional components; and (3) weight and gravity alteration. For each topic, we discuss how mechanical concepts have been commonly misapplied in peer-reviewed publications, the consequences of those misapplications, and how biomechanics, exercise science, and other related disciplines can collectively benefit by more carefully adhering to and applying concepts of classical mechanics.

1. Background

Biomechanics, as defined by Hatze (1974), "is the study of the structure and function of biological systems by means of the methods of mechanics" (p. 189). Biomechanics principally stems from two disciplines, mechanics and biology. The mechanical constructs employed have strict, unambiguous definitions (Thompson et al., 2008; IBWM, 2018). However, both the application of and language surrounding these constructs are not always adhered to in applied research reports, including those in exercise and sports medicine. As a result, a number of papers (Adamson and Whitney, 1971; Rodgers and Cavanagh, 1984; Knuttgen and Kraemer, 1987; Knudson, 2009; Winter and Fowler, 2009; Winter et al., 2015), editorials (Knuttgen, 1978; Winter and Knudson, 2011; Hering, 1900), letters to the editor (Winter, 2005; Ruddock and Winter, 2015), and even reviews (Winter et al., 2015; Knudson, 2018; van der Kruk et al., 2018) have addressed several of these mis- or ambiguous applications of mechanical principles; nevertheless, proper use of these, and other, key principles and terminology remains inconsistent. Here, we expound upon this prior work by discussing a few persistent misconceptions that have not been thoroughly explicated. To keep this article focused, we present these concepts with a specific emphasis on sports biomechanics, but we readily note that these also affect various other biomechanics sub-disciplines and related fields (e.g., exercise science, sports medicine, and kinesiology).

The intention of this article is not to single out individual researchers, sports, or disciplines, but rather to use these as concrete examples to enhance awareness of these far-reaching issues and to serve as a call to action for the field. There are three topics that we will address in this brief review, which we believe have not received enough attention in previous reviews and/or warrant re-emphasis: (1) joint reaction forces as they pertain to loads actually experienced by biological joints; (2) the partitioning of scalar quantities into directional components; and (3) weight and gravity alteration.

2. Joint reaction forces

Reaction force refers to Newton's third law, which states that for any action, there is an equal and opposite reaction. Therefore, joint reaction force should represent the force (reaction) equal and opposite to the force (action) that acts on the bones/tissues of which a joint is comprised. While this definition is intuitive, in the context of many peer-reviewed biomechanics studies and textbooks, it is also a source of potential confusion.

In biomechanics, joint forces come in two flavors. As detailed below, one type of joint force takes into account internal forces

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(i.e., from muscles, tendons, ligaments), while the other does not (Fig. 1). The latter joint force can be obtained with inverse dynamics (herein, we will refer to these as *net joint forces*). Alternatively, if one wishes to know about the former—the forces 'felt' by adjacent bones that make up a joint (herein, we will refer to these as *joint contact forces*)—then invasive measurement or musculoskeletal modeling is required to include muscle and other internal forces that will contribute to joint contact forces.

Unfortunately, there is no consensus as to which terms refer to which constructs. The discrepancies in definitions for a given term—especially joint reaction force—have been previously described, albeit briefly, by Zajac et al. (2002). While textbooks differentiate between the two different constructs of joint force, the terms used to describe these constructs are not consistent across the scientific literature (e.g., Table 1). These inconsistencies can have practical and inferential consequences that affect how biomechanical insights are interpreted and applied, both within and beyond the field (Knudson, 2018).

By interpreting a net joint force as a joint contact force, one may greatly underestimate the loads experienced by tissues at/within the joint, since forces from muscles and other internal tissues are not included (Fig. 1). For instance, the net joint force on the elbow is about 1–1.5 body weights during baseball pitching (e.g., Fleisig et al. (1995, 2006)), whereas the elbow joint contact force peaks between 4–7 body weights (Buffi et al., 2015). Similarly, during squatting, net joint force calculated from inverse dynamics on the knee is about 1–1.5 body weights (Gullett et al., 2009; Escamilla et al., 1998), whereas the joint contact force is much larger, about 2–3.5 body weights (Escamilla et al., 1998). The problem is that some researchers have used these net joint force estimates to interpret and speculate about overuse injuries (e.g., bone stress fractures), even though the actual tissue loading of interest is the joint contact force, or perhaps the force (or stress) within a specific tissue spanning the joint (e.g., on a specific muscle, ligament, or cartilaginous structure). Repetitive forces experienced by specific structures inside the body—not net joint forces—are what can lead to the accumulation of microdamage and eventual overuse injury (Gallagher and Schall, 2017; Edwards, 2018; Currey, 2002; Sasimontonkul et al., 2007; Nigg, 2001).

Table 1
Examples of different nomenclature for types of joint forces.

	Net joint force	Joint contact force
Zatsiorsky (2002)	Joint force	Bone-on-bone, contact force
Winter (2009)	Joint reaction force	Compressive load, bone-on-bone, joint contact force
Nordin and Frankel (2012)	–	Joint reaction force, joint force
Enoka (2015)	Resultant joint force	Joint reaction force
Yamaguchi (2001)	Joint reaction force	Joint contact force
Zajac et al. (2002)	Joint intersegmental force, joint resultant force	Joint contact force

A similar problem is prevalent in other exercise and sports medicine research as well, such as in running. Interestingly, this widespread issue has been largely overlooked because it is hidden tacitly within common methodological and logical assumptions, which are not often elaborated in methods and discussion sections of biomechanics research reports. A large swath of sports injury research over the last several decades has focused on ground reaction forces (GRFs), how these forces are transmitted (or

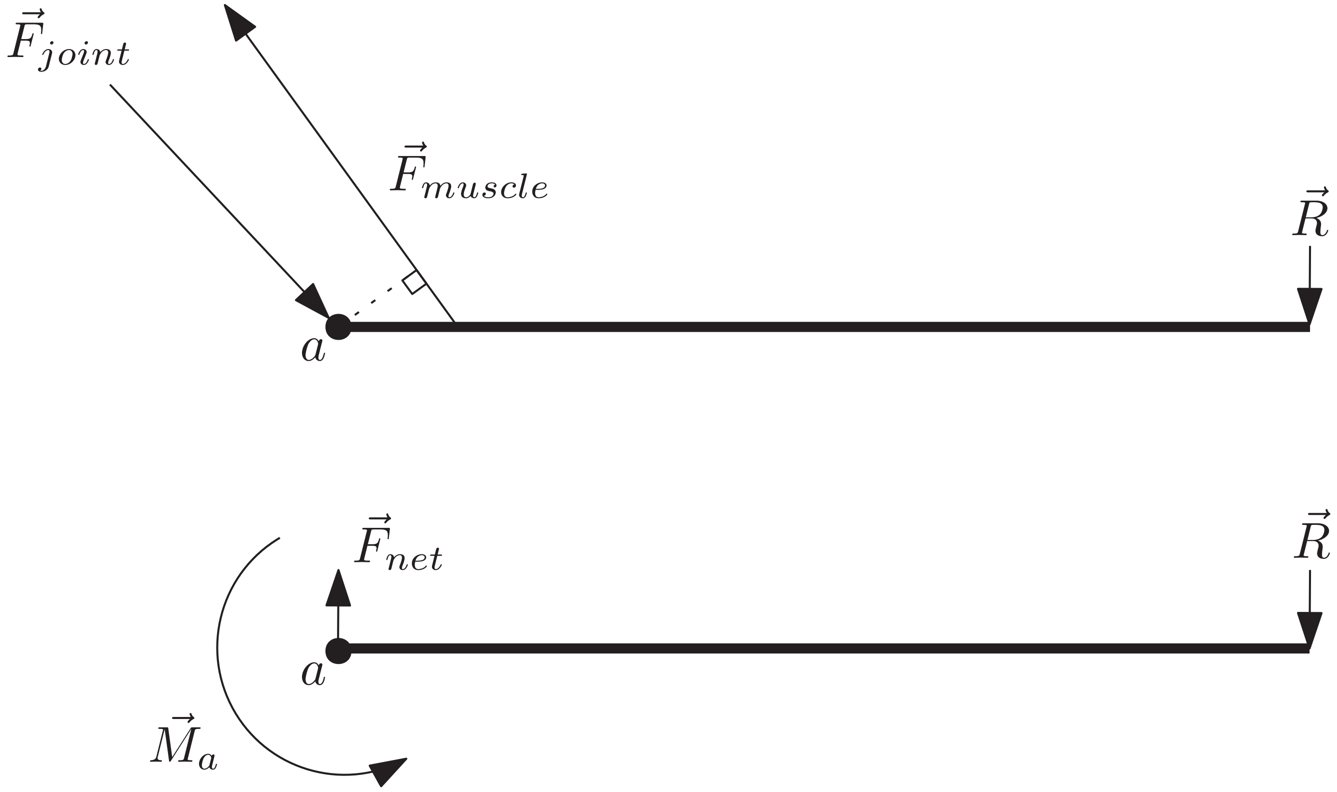

Fig. 1. An illustrative comparison between two types of joint force in biomechanics research reports. (Top) represents a joint force $\vec{F}_{joint}$ that includes muscle ($\vec{F}_{muscle}$) force, in addition to external and inertial loads. Musculoskeletal modeling techniques or internal force transducers are necessary to quantify this type of joint force. However, this joint force is reflective of what forces must be resisted internally, by both bone and connective tissues, such as ligaments. (Bottom) represents the net, or resultant, joint force, which can be calculated using inverse dynamics or static analyses without any knowledge of internal forces. The net joint moment, $\vec{M}_a$, is inclusive of the muscle force, and therefore, the magnitude and direction of $\vec{F}_{net}$ do not include internal forces. Note the different magnitudes and directions of the two joint forces, $\vec{F}_{joint}$ vs. $\vec{F}_{net}$.

attenuated) along a person's musculoskeletal system, and the types of overuse injuries that could potentially result from elevated GRF peaks or loading rates (e.g., at foot impact). The tacit logic is that increased GRF causes increased net joint force, under the presumption that increased net joint force increases microdamage or injury risk to bones, joints, or other internal structures (Collins and Whittle, 1989). Unfortunately, this logic conflates net joint force with joint contact force and neglects muscle forces (often the primary source of joint loading). During running, GRF peaks are only about 2–3 body weights (e.g., Nilsson and Thorstensson (1989)), and these result in net joint force peaks of similar magnitude (e.g., at the ankle). However, there is a considerable mismatch between net joint force and joint contact force. The joint contact forces are about 6–14 body weights and often occur at a different part of the running stride cycle than the peaks in GRF or net joint force (Sasimontonkul et al., 2007; Scott and Winter, 1990).

Thus, inferences and speculation about running overuse injury risks are often being made based on the wrong *joint reaction force* estimates, resulting in misleading or unfounded conclusions (Matijevich et al., 2019). Similar issues appear to exist in figure skating as well. GRFs and thus net joint forces are estimated to be on the order of 5–8 body weights during landing impacts. Researchers have then interpreted or suggested that these impact forces may be a main factor contributing to overuse injury (Saunders et al., 2014; Dubravcic-Simunjak et al., 2003). However, maximum joint contact forces at the ankle and knee during figure skating jumps are estimated to be much larger; in some cases, over 10 or 20 body weights (Kho, 1997). Furthermore, the peak joint contact force often occurs at a different time in the movement cycle than peak GRF (e.g., Kho (1997) and Dziewiecki et al. (2013)), again due to muscle contractile forces. For instance, high joint contact forces (e.g., 10–20 body weights) can occur during the take-off phase of the jump, when GRFs and net joint forces are relatively low. The sports discussed here were given as examples, but similar confusion between net joint force vs. joint contact force exists in other disciplines as well. The danger of this misconception is exemplified by Mills et al. (2009) study on gymnasts landing and Matijevich et al. (2019) study on runners, both of which demonstrate how decreasing GRFs (or GRF metrics, such as impact peaks) can actually correspond to greater joint contact forces; thus, the wrong choice of joint reaction force construct could lead to opposite conclusions.

Conflating joint contact force with net joint force (or similarly, with GRF) remains extremely prevalent within the biomechanics literature and literature of other related fields, such as exercise and sports medicine; this misunderstanding can impact sports and society. Regardless of whether this mix up is explicit or tacit, it can negatively affect scientific inferences, as well as misinform the design of experiments, interventions, and training regimens. These inferences may then affect popular press; for example, Olympics coverage speculating about the relationship between landing GRF peaks and overuse injuries in figure skating, and innumerable magazine articles written for runners, athletes, and coaches that make overuse injury assessments or recommendations based on GRFs (or correlated signals) without acknowledging the large disconnect between the GRF and the forces actually experienced by tissues inside the body. Likewise, there are a growing number of consumer wearables that seek to provide feedback, presumably on joint contact force or other musculoskeletal forces inside the body, to identify injury risks due to repetitive tissue loading. However, many of these devices actually provide summary metrics related to net joint force (e.g., vertical GRF impact peak or loading rate, tibial shock, or other accelerometer-based correlates of the GRF), which is not the relevant joint reaction force in this case (Matijevich et al., 2019).

Due to the discrepancies in the literature and terminology, and risk for future confusion, we urge that uses of joint reaction force (or any variation of joint force, for that matter) should be clearly defined and consistently used within a given piece. Our preferred nomenclature is to use net joint force for the inverse dynamics result because the modifier *net* serves as a useful reminder of the resultant nature of the value, and to use joint contact force because the term *contact* serves as a reminder that this represents the actual force experienced at the surface of the joint. Regardless of which terms authors choose to adopt, the key is to define them and use them consistently. Finally, to reiterate many biomechanics texts, net joint forces should not be interpreted as joint contact forces, except in special cases when internal forces are indeed zero or negligible.

3. Scalar and vector quantities

3.1. Speed and velocity

Velocity, one of the most basic measures in mechanics, is a vector quantity, which means that it contains both a magnitude and direction. The directional constituent of velocity makes it distinct from speed, which does not contain a direction; however, both measures describe how fast a body is moving.

Despite the distinction between speed (time rate of change of distance) and velocity (time rate of change of displacement), researchers have and continue to conflate the two measures (Doyle et al., 2007; Moghadam et al., 2011; Deschamps et al., 2013). For instance, in both swimming and running studies, some authors have used the term velocity instead of speed to describe the rate at which someone moves (e.g., Olbrecht et al., 1985; Wakayoshi et al., 1993; Ferro and Floria, 2013; Sousa et al., 2015). In doing so, the changes in direction that are inherent in each sport are ignored, and it is assumed that displacement is the same as distance traveled (Winter et al., 2015). For example, Wakayoshi et al. (1993) assessed swimmers' 400-meter times in a 50-meter pool. Velocity was reported using the time taken to complete the 400-meter swim, which consisted of going from the starting point to the other end of the pool and back for a total of four times. Because participants completed the swim where they started, their displacement would be zero, meaning their average velocity would be zero. Therefore, the values reported are average speed, not velocity (Winter et al., 2015).

Speed and velocity have clear and concise mechanical definitions that should be respected, especially within science and mechanics-based disciplines. If authors are intent upon using the term velocity in circumstances such as the example above, then perhaps 'mean magnitude of the resultant velocity' is more accurate, but we believe this term to be much less compendious than speed. Finally, although the misuse of velocity is a simple and seemingly benign mistake in most instances, it does have the potential to confuse readers, particularly those new to the field or those outside the field aiming to apply insights from biomechanics. To this end, we believe that accurate and concise communication is important to advance the field, avoid confusion, and set a good precedent (Knudson, 2018; Winter et al., 2015).

3.2. Directional power

Power—the rate at which mechanical work is performed—is a scalar quantity. This means that power has no direction, only magnitude. One of the formulas for finding instantaneous power (due to translation), which is relevant to biomechanics, is the dot product of the force acting on an object, $\vec{F}$, and the velocity of the point of application of the force, $\vec{v}$. Thus, non-zero power requires both a non-zero force and a non-zero velocity.

$$P = \vec{F} \cdot \vec{v} \tag{1}$$

Although $\vec{F}$ and $\vec{v}$ are both vector quantities, dot products produce a scalar quantity. Thus, the definition of power can be mathematically expanded into Cartesian coordinates

$$P = F_x v_x + F_y v_y + F_z v_z, \tag{2}$$

where $F_x,\ F_y,$ and F_z are forces and $v_x,\ v_y,$ and v_z are velocities in the $x,\ y,$ and z dimensions, respectively.

However, this is not always how power is used or computed in the literature. Specifically, sports biomechanists and other researchers who apply biomechanics to sport often split power into its 'components', as though it were a vector quantity; for example, reporting 'vertical' or 'horizontal' power (e.g., Morin et al. (2010), Buchheit et al. (2014), Lake et al. (2014), Mendiguchia et al. (2014)). In a strict mechanical sense, these quantities are not real powers. Because movement occurs in a three-dimensional Euclidean space, mechanical power is collectively the result of all three dimensions. Consequently, one- and two-dimensional calculations of power do not necessarily represent the actual rate at which work is performed within a system (van der Kruk et al., 2018). A mathematical example and rationale are provided in Appendix A.

While the above may be true, this does not preclude 'directional power' from being of occasional interest. Indeed, there are scenarios where biomechanists may be interested in these terms, and for good reason. For instance, if one is designing a prosthetic ankle, she may desire to understand the 'directional powers' of the human ankle to control independent motors in the prosthetic ankle. In such cases, perhaps authors may wish to use a term like *quasi-power* rather than power to distinguish that it is a projection.[1] In other cases—particularly in sports science—'directional power', like 'peak power', may not be as useful, interesting, or mechanically well-defined (Adamson and Whitney, 1971; Winter, 2005; Winter and Knudson, 2011; Knudson, 2009; Winter et al., 2015; van der Kruk et al., 2018). It therefore seems prudent to evaluate not only how mechanical measures are being calculated and reported, but also *why*; this burden is on authors to justify, particularly when deviating from classical definitions of power.

4. Weight and gravity

A person's weight is defined as their body mass multiplied by gravitational acceleration. Thus, their weight can be increased by either increasing their mass, increasing gravitational acceleration (which may require traveling to a more massive planet), or both.

Investigators have assigned different terms to the processes of experimentally increasing or decreasing a person's weight. For example, investigators have "simulated an increase or decrease in body weight" by attaching elastic bands to a pulley system to provide assistance to, or resistance against, an individual while performing vertical jumps (Pazin et al., 2013; Cuk et al., 2014). Because the authors studied a highly dynamic task, the inertial effects of increased body (mass-induced) weight would not have been reflected by the constant external force that was applied, which may affect the interpretation of some results.

Other terms have also been used to describe changes in body weight when simpler, more concise descriptions could be used. For instance, the addition of a weight vest to rugby players' training was described as simulated hypergravity (Barr et al., 2015). Of course, gravity was not changed, but mass was added to each subject to increase the system weight (i.e., person plus vest). The net result is also different than that of actual hypergravity (i.e., when the force of gravity exceeds that on the surface of the Earth); added mass would affect players' inertia, but not the gravitational acceleration. Thus, players would still fall at the same rate, but their mass and resulting dynamics would differ.

This same logic can be applied to weight and gravity reduction treadmills. These rehabilitation tools are used to exert an upward force on an individual to reduce axial loading during gait. As in the previous paragraphs, neither gravity nor weight is reduced; rather, force is applied elsewhere on the body to reduce the force that an individual needs to apply to the ground. Unfortunately, despite the fundamental mechanics being well-established, companies exploit these misconceptions for marketing purposes.

To avoid ambiguity of terms, we suggest that authors should clearly describe the intervention or exposure itself, and then compare/contrast this to what it is supposed to model or represent. Although hypergravity may sound cooler than weight vest, adopting the former terminology brings with it the potential for confusion and misinterpretation, since it implies that gravity has been altered when it has not been. Similar concerns have been raised about the use of microgravity and weightlessness as synonyms, and analogously how this can be cause for confusion (Chandler, 1991).

5. Conclusions

We have presented misconceptions related to joint reaction forces, scalar and vector quantities, and weight and gravity that are common in the sports biomechanics literature. These misconceptions may lead to errors in interpretation of data, theory development, sport training, or clinical interventions. Therefore, we believe it is important for the field to be candid about such misconceptions in the literature, to collectively work to fix/clarify these issues, to educate the next generation of biomechanists, and to be actively engaged in communicating biomechanics to those outside the field to ensure scientific understanding is being faithfully translated and applied to sport and societal issues. As biomechanists, we must be diligent in staying true and grounded to the mechanical roots from which our discipline is derived, and in doing so, avoiding the aforementioned misconceptions. Yet, in some cases, and so long as the authors are aware and transparent, perhaps straying from purely mechanical roots may be useful and permissible; though, the rationale for such deviations should be explicitly justified. Nevertheless, we are hopeful that future papers and biomechanists are able stay as true as possible to our mechanical roots.

Declaration of Competing Interest

The authors declare no conflicts of interest.

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Appendix A. Example of why power 'components' are not vector quantities

In a mathematical sense, omitting dimensions in power calculations can misrepresent the true amount of work being done because power 'components' do not behave like vectors. Consider the force and velocity vectors $\vec{F} = 1\hat{\mathbf{i}} + 2\hat{\mathbf{j}} + 3\hat{\mathbf{k}}$ and $\vec{v} = 3\hat{\mathbf{i}} + 2\hat{\mathbf{j}} + 1\hat{\mathbf{k}}$, respectively. If the terms of the dot product are taken as 'components', the vector would be $3\hat{\mathbf{i}} + 4\hat{\mathbf{j}} + 3\hat{\mathbf{k}}$. Now,

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[1] Similar recommendations have been made for joint stiffness that is assessed as the derivative of the net joint moment–angle relationship (Latash and Zatsiorsky, 1993; Rouse et al., 2013).

consider a rotation about the *z*-axis, which would utilize the transformation matrix *T*.

$$T = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

After transforming $\vec{F}$ and $\vec{v}$, the new vectors would become $\vec{F}' = -2\hat{\mathbf{i}} + 1\hat{\mathbf{j}} + 3\hat{\mathbf{k}}$ and $\vec{v}' = -2\hat{\mathbf{i}} + 3\hat{\mathbf{j}} + 1\hat{\mathbf{k}}$. Thus, the 'components' of the calculated power using the transformed vectors would be $4\hat{\mathbf{i}} + 3\hat{\mathbf{j}} + 3\hat{\mathbf{k}}$. If the 'components' of the original power solution were to also be rotated about the *z*-axis, it would yield a different solution $(-4\hat{\mathbf{i}} + 3\hat{\mathbf{j}} + 3\hat{\mathbf{k}})$. Therefore, because the 'components' and their sum do not rotate like a vector or maintain the same solution after a transformation, each 'component' does not necessarily have a true physical meaning.

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