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Biomechanics: 40 Years On

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Abstract

In the last 40 years, biomechanics has progressed significantly as a subdiscipline within kinesiology. The development of national and international societies dedicated to biomechanics and the increase in the number of scientific biomechanics journals has led to a growth in the biomechanics community. In the last few decades, the research focus in biomechanics has broadened substantially. With this diversity of focus, there have been many novel developments in new technologies used in biomechanics. Biomechanics has become an integral subdiscipline that has interfaced with several other areas in kinesiology and has contributed significantly to enhancing the knowledge base in all areas. Much of the development of biomechanics has resulted from improvements in the technology used in movement research. Although it may be overreaching to say that biomechanics can solve many human movement problems, the technology has allowed researchers to at least answer more comprehensive questions and answer them in greater depth.

Keywords

markerless tracking, musculoskeletal injury, technology

Disciplines

Biomechanics | Expeditionary Education | Health and Physical Education | Kinesiology

Comments

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Perspectives on the Academic Discipline of Kinesiology

David Anderson and Richard Van Emmerik (eds.)

Biomechanics: 40 Years On

J. Hamill, K. M. Knutzen and T.R. Derrick

As a sub-discipline within the field of kinesiology, biomechanics is still a relatively new area of study. With roots in physical education in the 1970s (Nelson, 1973), biomechanics was initially concerned with the study of sports techniques. Subsequently, biomechanics has developed into an integral part of the study of animate movement as a stand-alone area of research and in combination with other disciplines within kinesiology and external to kinesiology. However, compared to other sub-disciplines within kinesiology, biomechanics is a new area that is steadily growing with the creation of several large national and international professional societies, the development of a large cohort of biomechanists, and a significant body of literature.

The development of two major international societies (i.e., the International Society of Biomechanics and the International Society of Biomechanics in Sports) along with numerous national societies (e.g., American Society of Biomechanics, Canadian Society of Biomechanics, European Society of Biomechanics, etc.), technical groups affiliated with these societies (e.g., Footwear Biomechanics Group, 3-D Analysis of Human Movement, Computer Simulation, International Shoulder Group, Motor Control Group) and groups for specific areas of study within biomechanics (e.g., the International Society of Electrophysiological Kinesiologists, Foot and Ankle Research, etc.) have led to the development of biomechanics as a sub-discipline of kinesiology. Each of these societies have either annual or biennial conferences/symposia that comprise between 500 to 2000 attendees. The World Congress of Biomechanics, while not a society, supports a conference every four years that has an attendance of approximately 4,000 to 6,000 attendees.

While biomechanics as a sub-discipline originated from mainly from Physical Education, the development over the last few decades led to a community of biomechanists in very diverse fields within and outside the field of kinesiology. For example, at the most recent World Congress of Biomechanics in Dublin, Ireland in 2018, there were 27 concurrent sessions, each with a different topic area in biomechanics. Some of these topic areas are listed in Table 1. These different topic areas are an indication of the diversity of the areas of study within biomechanics.

Table 1. Topic areas illustrating the diversity of content in biomechanics.

sport biomechanics	biomechanics of aging
clinical biomechanics	muscle mechanics
postural biomechanics	computer simulation and modeling
spine biomechanics	footwear biomechanics
dental biomechanics	cardiovascular biomechanics
reproductive biomechanics	ergonomics
orthopedic biomechanics	tissue biomechanics
musculoskeletal biomechanics	forensic biomechanics

Another reason for the growth of biomechanics in the last few decades has been the increase in the number and variety of professional journals that publish studies in which biomechanical analyses are a key ingredient. Prior to the rapid growth of biomechanics in the 1970s, journals from the research areas of physics or engineering would have an occasional paper that would contain data considered in a biomechanical analysis. Presently, there are a number of journals that relate specifically to biomechanics (e.g., Journal of Biomechanics, Journal of Applied Biomechanics, Clinical Biomechanics, etc.) and many other more interdisciplinary journals (e.g., Medicine and Science in Sport and Exercise, Journal of Sports Science, Journal of Health and Science, etc.) that also publish biomechanics research papers. There are also a number of journals specific to particular topic areas that publish research papers in biomechanics (e.g., Foot and Ankle Research, Journal of Orthopedic Research, Journal of Applied Physiology, etc.). However, there are other journals not specifically considered to be concerned specifically with biomechanics that have included biomechanics research (e.g., Nature, Journal of Applied Physiology, Journal of Experimental Biology, Computers in Science and Biology, etc.).

The remainder of this chapter will deal with the developments that have occurred in biomechanics subsequent to the formative years of the discipline, the types of questions that may be answered using a biomechanics paradigm, the current 'hot' topics of biomechanics research, the integration of biomechanics with other sub-disciplines in kinesiology and the future directions of biomechanics.

Key Developments in Biomechanics Over the Last Few Decades

As stated previously, biomechanics initially developed in Physical Education or Kinesiology departments with the analysis of sport techniques as the main focus. However, research in biomechanics broadened considerably to include a greater diversity of research topics including clinical/injury related research. With the expansion of the types of research questions that used the usual biomechanics techniques (e.g., motion capture systems, force platforms, electromyography) and biomechanical analyses (e.g., kinematics, kinetic, inverse dynamics, optimization, and forward dynamics), biomechanics programs are not presently confined to Physical Education/Kinesiology departments but have expanded to, for example, mechanical, civil and industrial engineering, physical and occupational therapy, and biology departments.

Biomechanics has become relevant to this diverse set of fields because it treats the body and the environment holistically. It does not simply treat the body as a mechanism to be engineered – although the body does share some traits with machines that make this comparison useful at times. Biomechanics does not simply treat the body as a static anatomical specimen – although this also plays a role in the biomechanics toolbox. Rather, biomechanics treats the human body as a dynamic biological structure that is constrained by its environment but also leverages that environment in the struggle for optimality. For example, human movement is certainly limited by the strength of muscle and bone tissue, but these very dynamic tissues increase in strength when these limits are repeatedly approached. No machine or cadaveric specimen will react in such a manner. It is becoming more evident to those outside of biomechanics that this holistic approach is needed to insure we understand how to maintain the human body in prime condition.

The variety of types of departments in which biomechanics has found a home, creates the necessity to increase the knowledge base of biomechanics. It is clear to biomechanists that the "bio" and "mechanics" need to be integrated. In his book "The Movement of Animals" (1680-81), Borelli incorporated numerous figures portraying the structure and function of the body. Until recently this approach comprised much of the knowledge base for our discipline. However, it is no longer adequate to our needs. In a world of increasing quantification, biomechanists now need additional methods to help discern the details of human motion. Graduating students now are required to have knowledge in the areas of statics and dynamics, electronics, numerical analysis, mechanical and muscle modeling, computer optimization and simulation and statistics along with the usual biomechanics data collection and analysis laboratory techniques. As a result, the research questions that are now being asked were far more in depth than those from the 1979s of 1980s.

Another development that has occurred in the last several years is the expanded placement of biomechanics graduates. In the early years of biomechanics as a sub-discipline, graduating doctoral students generally proceeded directly to an academic position. Now, it is almost expected that a graduating doctoral candidate continue their studies as a post-doctoral researcher if they seek a quality research position. In addition, the type of position that newly graduating doctoral candidates have available to them has expanded. Rather than only academic positions, candidates may proceed to occupations conducting research in industry, hospitals or private laboratories. The training that new graduates have undergone has magnified these opportunities.

The greatest change in biomechanics in the last few decades has been the development of new technologies that are now used in research. Quantification of various aspects of a biological system is a primary goal of biomechanics and advancing technology has provided the impetus to biomechanics as it has moved from simply describing movement parameters to exploring multi-dimensional components of human motion. As biomechanists, we must be able to record motion and forces acting on the body. We have had the knowledge of how to do this for a relatively long period of time, however, it was not practical at a large scale until the commercial development of the force platform in the 1970's and the automated motion capture systems in the early 1980's. Once, these two items were fully developed and integrated with computer systems, the post processing of human movement data expanded exponentially.

The changes in technology in the analysis of human movement parameters has opened new avenues for the evaluation of complex movement problems allowing for an analysis of more comprehensive data sets. Human movement is complicated and biomechanical measurement and methods have been made much easier by technology that allows for the evaluation of large data sets. The field of biomechanics is growing concomitantly with advances in technology because new technology provides researchers with tools for providing solutions to more advanced human movement problems.

Ferber and associates (2016) identified advances in data science that have contributed to understanding gait biomechanics. These include advances in computers, motion capture equipment, force instruments, inertial sensors, and EMG in addition to data analysis techniques. These authors point to challenges in biomechanics and look to future development of tools and sharing of data across gait labs to allow for analysis of large quantities of data.

Computers

Changes in computer technology have significantly advanced innovation and efficiency relating to the collection and analysis of biomechanical data. The discipline has migrated from using large mainframe computers to minicomputers to microcomputers. Today, we have significant computer power in portable computers that provide significantly greater accessibility to the research environment. The power and speed of computer processing has allowed for onsite data collection and processing. This has been accompanied by significant advances in computer software and hardware interfaces. Control of data collection and processing has also advanced with the use of specialized software or specific scripts or toolboxes from mathematics or engineering software applications such as MatLab (The MathWorks, Inc.).

Computer technology has also facilitated higher levels of computing with greater volumes of data. Computer simulation of movement, modeling, and finite element methods are more feasible with the improvements in computer processing speed and accuracy. Advances in computer tomography (CT) and magnetic resonance imaging (MRI) have improved modeling by providing more accurate information about bone and bone properties and structure (Ren et al., 2014).

Various statistical methods such as Functional Data Analysis (e.g., Harrison et al., 2007), Statistical Parameter Mapping (e.g., Pataki et al., 2010) and Principal Component Analysis (e.g., DeLuzio & Astephan, 2007) have been applied to biomechanical data because of computer improvements. Finally, enhanced computing power has opened exploration of topics evaluating multi-dimensional components and has allowed researchers to explore biomechanical, physiological, and neurological characteristics to provide a more thorough study of human motion.

Motion Capture

In the 1970's and 1980's, video-based systems capturing two or three planes of motion were the primary tools used in a biomechanical analysis. This was a technology transition from earlier hand digitization of film to video and computerized data processing. Motion capture systems have seen significant technological innovation and it continues to advance at a rapid pace. There are many systems now that utilize multiple infrared cameras to track reflective markers or pulsed LEDs placed on segments of interest. The cameras are very accurate, there is limited constraint to motion and the capture frequency is much higher than in the past. In a typical research study using an optoelectronic motion tracking system, many of the procedures still follow the traditional data collection protocols. Data are processed within the cameras and then digitally transferred to to the computer at near real-time speeds. This eliminates the previously used digitization process. Specialized software (e.g. Visual3D, C-motion, Inc., Rockville, MD) including open-source software can now be used to normalize, scale, and filter the data to compute linear and angular kinematics. Coupling kinematic and kinetic data can result in the calculation of joint kinetic data using inverse dynamic methods.

Measurement of Forces

The measurement of ground reaction forces with the force platform has taken biomechanics in a direction where linear and angular kinetics can be calculated with greater accuracy. One of the issues with the force platform is the lack of portability with most platforms located in a laboratory setting. Laboratories often use multiple platforms placed in a walkway to record multiple steps in gait studies. More recently, force platform technology has advanced to allow for more portability. In the last several years, force platforms have been incorporated into treadmills and stairs. Instrumented treadmills are now commonplace in research laboratories thus increasing the number of cycles that can be accumulated. In studies where stair climbing is investigated, instrumented stairs give greater insight into the forces applied to mount the stairs which is particularly useful in clinical studies.

Electromyography (EMG)

EMG has been used in biomechanics laboratories for many years. The techniques used have included surface and in-dwelling electrodes. These electrodes have generally been wired from the electrode on the participant to an amplifier that interfaces with a computer. The transition from these types of 'wired' electrodes to telemetry electrodes has allowed the research to develop a great range of questions and has not limited the research to a laboratory setting. In many cases, the newer EMG electrodes also contain accelerometers, gyroscopes, and magnetometers.

Sensor Technology

Motion capture using non-optical units are rapidly advancing in the technology area. Inertial Movement Units (IMU) can contain three-dimensional accelerometers, gyroscopes, and magnetometers. These units are wireless and becoming lighter and they allow for collection and analysis of time series data in activities such as diving (e.g. Walker et al., 2019). The units can collect angular velocity and acceleration data.

The IMU has proved to be a useful technology in the clinical setting where it has been successfully used to measure various movements in an outpatient setting (Zucchi, et al., 2020). They can be triaxial with the potential to measure accelerations along three axes and angular velocities in three planes. If a magnetometer is also included, the sensors can provide angular velocity, angular acceleration, and three-dimensional orientation of the segment (see Camomilla et al., 2018). Wearable sensors have been used to collect data outside the lab in settings impossible to replicate in the laboratory. For example, Clermont and associates (2019) used an IMU and a GPS-enabled watch to examine fatigue during marathon running.

One emerging sensor technology is the fiber Bragg gratings (FBG) which are small, biocompatible, immune to electrical interference, high sensitivity, high dynamic range, and with multiplexing capability (Al-Fakih et al., 2012). A light source is transmitted through the FBG and a narrow band is reflected back. This is used to measure the strain in the material. The FBG is seen as an alternative to strain gauges or piezoelectric sensors. This sensor has been used in aeronautics, the automotive industry, and in civil engineering applications (Al-Fakih et al., 2012).

Imaging

Imaging technology has improved significantly over the past forty years, creating new opportunities for biomechanical research. Fleming (2019) has summarized advances which will lead to more accuracy in our ability to assess bone, cartilage, and other structures. Advances in radiography and computed tomography such as biplanar video-radiography can track three-dimensional joint motion in vivo and be used to track progression of arthrosis. Ultrasound has improved to allow closer examination of muscle contraction. In vivo muscle structure, muscle fiber movement have provided valuable new information. Improvements in magnetic resonance imaging provides three-dimensional images of features such as cartilage thickness and ligament and tendon vascularity. Lastly, dual x-ray fluoroscopy has enabled researchers to investigate the movement of individual bones in motion.

'Big' Questions That May Be Answered Using a Biomechanics Paradigm

There are several significant questions that the biomechanics paradigm is useful in answering: 1) the mechanisms of injury; and 2) the development of rehabilitation devices. We will only consider these two questions but recognize that there are many others within the diverse sub-areas of biomechanics that lack relevance to society in general.

There is a long history of the study of injuries (particularly during running) in biomechanics. Much of this research has used kinematic or kinetic analysis, for example, to discern differences in runners pre- and post-injury (Mahieu et al., 2006), injured runners versus non-injured runners (Hamill et al., 1999) or runners with certain types of injuries (Heiderscheit et al., 2002). A particular emphasis in these early studies was on pronation (calcaneal eversion) as a cause of many lower extremity injuries including tibialis posterior tendinitis, Achilles tendinitis, patellofemoral disorder, iliotibial band syndrome, and lower extremity stress fractures among others. Even though there is no clinical definition, 'over-pronation' was considered to be a root cause of these injuries. Hintermann & Nigg (1998) concluded that the link between pronation and injury was tenuous and many mechanisms thought to cause overuse injuries to the lower extremities are still not well understood.

In the investigation of injuries in biomechanics, a central feature of the research has been concerned with tissue damage. When examining the potential for tissue damage, the mechanical load on the tissue is only part of the problem. An injury occurs whenever the load on the tissue exceeds the ability of the tissue to withstand that load. Biomechanists can estimate the load very ably but less so at estimating the tissue strength. There are bioengineering techniques available that allow us to estimate quantities such as ultimate strength, brittleness, stress-strain relationships, cycles to failure, and probability of failure. These are important characteristics of many biological tissues but we often simply rely on the change in force as a measure of the potential for injury. It is imperative to move from relative measures to absolute estimates of tissue damage. For example, running is suggested to produce about 2000 microstrain of deformation in the tibia (Milgrom et al, 2003); however, the fracture strain in bone is about 24,000 microstrain. Given this information alone, it is difficult to see how running could ever cause a stress fracture. Yet runners routinely get stress fractures because small changes to the magnitude of the force can result in large non-linear reductions in the cycles to failure (Edwards et al., 2009). We also rarely consider the time history of the loading. The repair process required from previous loading may temporarily increase porosity in localized regions of the bone, leaving the bone susceptible to the loads placed on it.

The estimation of the proximity of loads to tissue tolerance requires us to move from generalized to individualized models. The rigid body model that is commonly used, is specific to the individual, but the more detailed models are often generalized models that we may scale to the individual but retain material and geometric properties of the original model. Scanning technology and methods that would allow us to customize our models to the individual are available but are costly and time consuming. In general, our ability to study groups of individuals far surpasses our ability to study a single individual. Groups of participants may contain subgroups of individuals that employ differing strategies to accomplish the goal of reducing the load on the human body. These differing strategies may be in opposite directions such that the group mean shows no difference in the dependent measure. Of course, our current unsuitability to study individuals has implications in the clinical/rehabilitative setting or for individuals that have abnormally sized or shaped anatomy or have damaged structures. Certainly, progress needs to be made in this area to improve the ability of biomechanics to influence the clinical/rehabilitative setting.

In the development of rehabilitation devices, the work in biomechanics has included the development of ergonomic wheelchairs and prostheses for both the upper and lower extremities. In wheelchair research, biomechanical studies in wheelchair sports mainly aim at optimizing sport performance or preventing sport injuries. The sports performance optimization research has been approached from an ergonomic in addition to a skill proficiency perspective. Injury issues have been addressed in wheelchair sports mainly because of the extremely high prevalence of repetitive strain injuries such as shoulder impingement and carpal tunnel syndrome. Understanding the musculoskeletal mechanism of injury has been considered through both experimental and modelling approaches emphasizing the force generation and muscle activity patterns (Vanlandewijck et al., 2012). Much of the research on wheelchairs has been related to the types of injuries that result in individual's use of wheelchairs.

Current 'hot' Topics

The current 'hot' topics in biomechanics revolve around technological developments. There are two primary areas that we will discuss regarding these developments: 1) musculo-skeletal modelling and computer simulation; and 2) motion capture marker-less tracking.

Technical advancements in data collection have been swiftly followed by advancements in computer modelling. Previously, kinematic and kinetic data were combined with a segmented rigid body model to estimate the torques required of the joints that carry out a desired movement. As a gross measure of joint kinetics these data were invaluable; however, more precise measures could be attained by serially connecting the output of the rigid body model to the input of a musculo-skeletal model that would allow us to distribute the joint torques to individual muscles. Detailed musculo-skeletal models have been developed using a variety of platforms. One of the more popular programs is an open source program call OpenSim (Seth et al., 2018). The output from these analyses are often combined with optimization techniques to overcome the problem of muscular redundancy. Tissue level modelling has been used to estimate forces in tendon, ligament, and other connective tissue. Additional detail is achieved using finite element models of the tissues themselves. Stress and strain distributions could be compared to tissue tolerance levels to investigate the potential and even the probability of injury. Multi-scaled modelling techniques like these have advanced our field from looking primarily at the external loading environment to probing the details of the tissues that are being damaged.

It was necessary to develop musculo-skeletal modelling techniques to advance the field of biomechanics because of the difficulty measuring tissue level loads *in vivo*. A solution to this difficulty emerged in the form of simulation (Mansouri & Reinbolt, 2012). What we could not accomplish with a physical protocol we could achieve by simulation. In a forward-dynamics simulation, a carefully simplified representation of a human body or part of a human body could be constrained by a virtual environment and then instructed to perform as relevant parameters are estimated. Simulations overcame limitations such as internal tissue measurement, hazardous or impossible experimental protocols, and non-optimal human performances. Even though the assumptions inherent in any simulation need to be scrutinized in detail, the results allow us to ask questions that could not otherwise be asked.

The second area in which there has been considerable advancement over the last few years is in marker-less tracking of kinematic data. There has been recent interest and progress in the measurement of kinematics *in situ* because our ability to collect data outside the laboratory setting has always been limited. However, marker-less tracking of kinematic data is becoming a viable alternative to our standard method of camera based kinematic data collection. Marker-less motion capture offers an alternative method for the collection of kinematics that presents several practical benefits over marker-based systems. For a comparison of marker and marker-less tracking, see Figure 1 for a comparison of the computation of lower extremity angles.

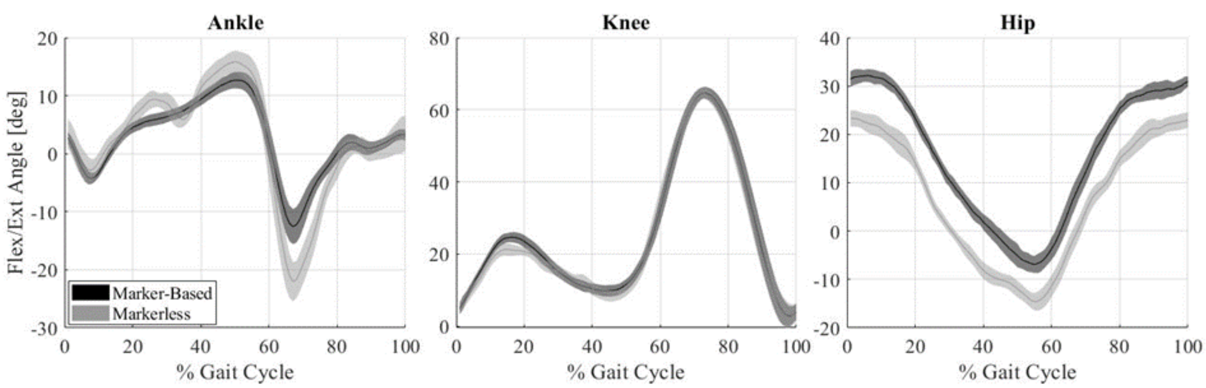

Figure 1. A single participant comparison of the sagittal view lower extremity angles computed from marker and marker-less data collections. The shaded areas around each solid line indicate the standard deviation over several trials. (This figure was provided by Robert Kanko of Theia Markerless, Inc.).

The collection of kinematic data has been hindered by the inherent flaws of marker-based motion capture systems which have long been the standard method for the collection of kinematic data. These limitations include lengthy data collection times, the requirement of highly skilled experimenter capable of accurate marker placement, dedicated laboratory space, and the intrusive nature of the technology and experimental protocols on the participant. This technology requires markers to be placed on participant's palpable anatomical landmarks, a process that requires 20-30 minutes and causes the resulting data to be susceptible to inaccurate and inconsistent marker placement. Standardized protocols have been shown to reduce undue variability in data collected on the same subject at different laboratories by different operators (Gorton et al., 2009); however, some inter-operator variability persists even when an identical collection protocol and the same laboratory are used (Maynard et al., 2003). Marker-based motion capture technology requires a dedicated laboratory space or enclosed environment, which is a significant barrier to the collection of data outside of research facilities. In addition, participants are required to wear minimal, skin-tight clothing to enable researchers to attach markers to their body. In combination, the unfamiliar laboratory environment, physical and social discomfort due to the clothing and markers reduce the reliability of the data collected using marker-based motion capture.

With advances in computer-vision techniques and the increased availability of computational power, marker-less motion capture systems have undergone significant improvements in processing time and accuracy and are now available as commercial products. These systems use a machine learning-based marker-less motion capture software that uses a two-dimensional video data from an array of standard video cameras to perform a three-dimensional pose estimation on human participants. Since the motion capture system does not rely on skin-based markers, participants are not required to wear minimal and skin-tight clothing, and instead wear their own clothing. Thus, participants may be significantly more comfortable and able to perform physical tasks more naturally leading to more ecological data. Furthermore, the marker-less system is not limited to use in laboratory spaces, allowing data to be collected in real-world environments that cannot be replicated in the laboratory. Lastly, since the marker-less system is not reliant on markers being placed incorrectly or inconsistently, there can be less variability introduced to kinematic measurements across sessions or operators (Kanko et al., 2020).

Integration of Biomechanics with Other Sub-disciplines in Kinesiology

In the last few decades, biomechanics has become an integral part of kinesiology research both as an independent area and as complementary to the other sub-disciplines in kinesiology. In addition, biomechanics has become an integral part of research in several other disciplines such as biology, anthropology, engineering, ergonomics, etc. Several example studies from the sub-disciplines of physiology and motor control in kinesiology and from the disciplines of anthropology and engineering will be presented to serve as examples of this integration.

Physiology

A logical area with which to integrate within kinesiology is exercise physiology. Pioneering work in the 1930s by Fenn (1930) and Elftman (1939) combining motion of the center of mass with the metabolic energy estimates during running provided a baseline for many subsequent studies. Determining the mechanics and the subsequent metabolic cost of running and walking under many conditions and with multiple perturbations has been prevalent in the biomechanics literature. There are numerous biomechanical and physiological studies in the literature comparing different locomotion states: walking and running (Ounpuu, 1994); uphill, level and downhill (Vernillo et al., 2016); males and females both walking and running (Ferber et al., 2003); older and younger individuals (Freedman-Silvernail et al., 2015), physically fit and sedentary (Morris et al., 2017), performance running footwear (Vercruyssen et al., 2016), different locomotor speeds (Weyand et al., 2000), running and cycling (Millet, 2009) and many others.

One particular area of interest has been the biomechanical factors that affect running economy which has been defined in the biomechanics context as the energy demand for a given velocity of submaximal running, and is determined by measuring the steady-state consumption of oxygen and the respiratory exchange ratio (Saunders et al., 2004). This topic has been of continuing interest for many years in biomechanics as it relates to, for example, running speed and performance. It was reported that increased EMG of working muscles and the associated increase in power output may partly explain energy expenditure increasing with running speed (Kryolainen et al., 2001). Inferior performances in running economy by some of the athletes may also be explained by poor running technique. However, they found no exclusive biomechanical parameters that explained running economy. Other studies have investigated similar relationships in terms of modifiable biomechanical parameters that could affect running economy and the possible training-induced changes in running economy and running biomechanics (Moore, 2016). This author suggested several factors such as lower limb, trunk and upper limb kinematics and kinetics during propulsion that may be modifiable which could influence running economy. An interesting perspective on running economy and biomechanics considered the energy storage and utilization of elastic energy in tendons (Scholz et al., 2008). In this paper, the moment arm of the Achilles tendon was determined and running economy was measured. A strong relationship was found between smaller muscle moment arms and lower rates of metabolic energy consumption.

A particular extension of the relationship between running economy and biomechanical modifications has been in the development of footwear to improve performance. Hoogkamer and associates (2016) showed that small (1-3%) changes in running economy quantitatively affected distance running performance by adding weights of 100 to 300 g per shoe. The study of running economy has been the case particularly with respect to the development of high-performance running footwear. In the quest for the sub 2-hour marathon, newly developed running shoes were tested to determine if these shoes could reduce the energetic cost of running compared to established footwear (Hoogkamer et al., 2017a). It was reported that these new shoes could reduce the cost of running on average by 4%. A further study by this same research group outlined an approach that integrated exercise physiology and biomechanics to reduce the metabolic cost of running (Hoogkamer et al., 2017b).

Overall, the integration of biomechanics and physiology is very important for both sub-disciplines. In measuring whole-body mechanics, it is difficult to ascertain a complete answer to most questions without the influence that the biomechanical parameters my have had on the physiology of the system.

Motor Control

The integration of biomechanics and motor control has been very fruitful for both sub-disciplines, expanding the types of questions that may be asked. While biomechanics as a sub-discipline has often been accused of describing the outcomes of movements without determining how the movements are controlled, the addition of a motor control perspective has added the element of how movements are controlled. Over the last few decades, the use of a Dynamical Systems approach to research has become a significant interest to both sub-disciplines. Within this framework, a number of methodologies have been used in the integration of biomechanics and motor control research including the analysis of, for example, relative phase (Ferber et al., 2005), fractal properties (Duarte & Zatsiorsky, 2000), uncontrolled manifold concept (Scholz & Schöner, 1999), maximum Floquet multipliers (Dingwell et al., 2007), detrended fluctuation analysis (Dingwell & Cusumano, 2010), Lyupanov exponents (Terrier & Deriaz, 2013), recurrence quantification analysis (Haddad et al., 2008) and entropy (Preatoni et al., 2010). These techniques have been used in many difference studies with topics such as overuse injuries, sports, athletic footwear, developmental changes, posture, learning, etc.

A particular area of interest for both biomechanics and motor control is the study of movement coordination and coordination variability from a Dynamical Systems perspective. Coordination has been defined as the selective activation of degrees of freedom in such combinations that their united action will result in organized motor activity (Weiss, 1941). Coordination variability is often quantified as the between-cycle or between-trial standard deviation of the coordinated movement. Rather than viewing variability as noise or error, variability has been suggested to be functional and essential to adaptation, exploration and learning (Newell & Corcos, 1993). The functional role of variability in movement coordination has been a central aspect in the dynamical systems approach being critical in movement coordination and the identification of loss of functionality (Fonseca et al., 2020; Hamill et al. 1999; Van Emmerik et al., 1999; Preatoni et al., 2013).

Bernstein (1968) described the redundancy in the number of available components or degrees of freedom to perform a task enabling a system, with multiple degrees of freedom, to have different solutions for a particular task. During running, the motions of the body's segments are performed in a cyclic manner. Even in a well-learned movement such as running, the motions of the body segments will vary somewhat. In overuse injuries in running, several researchers (Heiderscheit et al., 2002; Hamill et al., 1999, 2006; Miller et al., 2008) examined coordination of the lower extremity segments and their over multiple stride cycles. Hamill et al. (1999) proposed that a higher coordinative variability was the healthy state while a lower coordinative variability was the unhealthy state. They submitted that, with the greater coordination variability, there would be many different solutions to move utilizing different degrees of freedom. In the unhealthy or injured state, the reduced coordination variability, indicate a limited number of solutions indicating a narrow range of pain-free running. A major limitation of these studies, however, was that they were all retrospective in nature.

Coordination variability has been analyzed in terms of the coordination and variability of the coordination of body segments. While there are a number of methods that can be used for such studies, the most prevalent methods in the literature to investigate coordination and variability are vector coding (e.g., Sparrow et al., 1987; Tepavac & Field-Fote, 2001), modified vector coding (e.g., Heiderscheit et al., 2002), discrete relative phase (e.g., McDermott et al., 2003) and continuous relative phase (e.g., Hamill et al, 1999). Of these methods, the modified vector coding and continuous relative phase approaches are most prominent in the literature (see Figure 1). Each of these techniques has benefits and limitations and their use is dependent on the nature of the research question. The methods for the calculation of these methods is presented in detail in Van Emmerik et al. (2013).

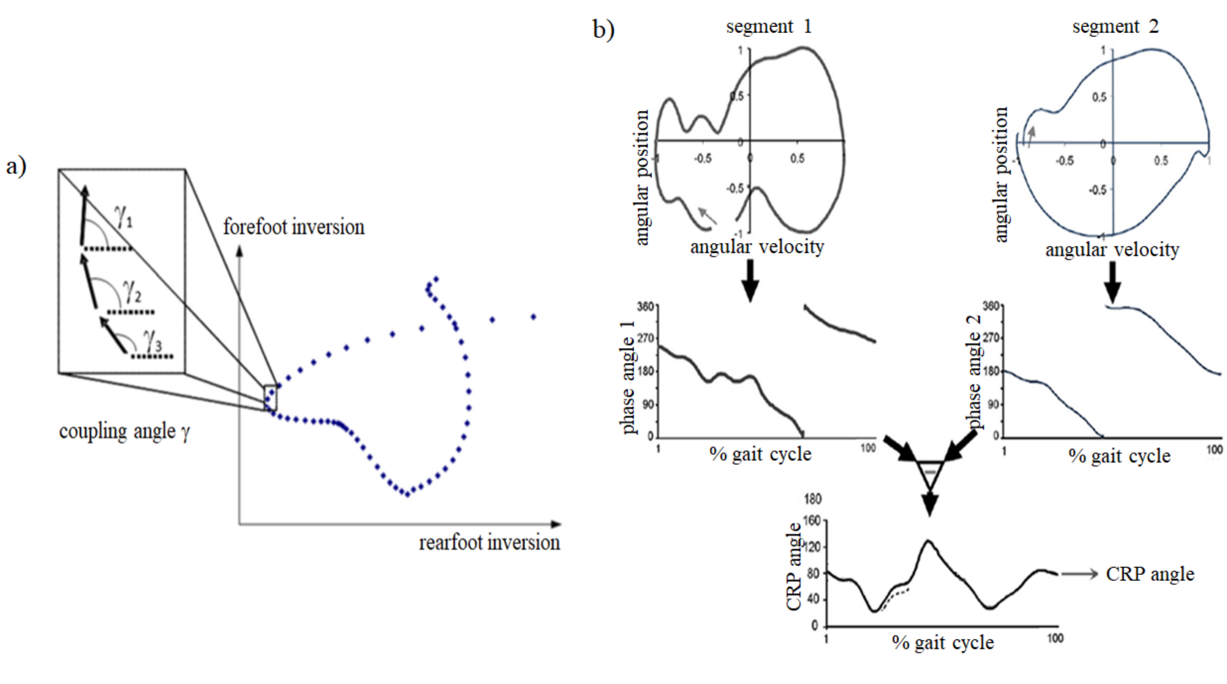

Figure 2. Examples of the calculation of approaches to the analysis of inter-limb coordination: a) modified vector coding: In the modified vector coding technique, a coupling angle is determined from the angle formed from a line between two points on an angle-angle plot and the right horizontal (note that these angles form directional data) forming the coordination angle – the variability of the coupling angle is determined using directional statistics (Batschelet, 1981). b) continuous relative phase (CRP): in CRP analysis, the coupling angles from the phase plots (position versus velocity) of two oscillators are subtracted to form the CRP angle or the coordination angle – coordination variability of determined as the standard deviation from the CRP angles of multiple cycles.

Biology

The interaction of biomechanics and biology has been important in the study of both human and animal locomotion. Essentially, biology questions are answered using the tools or techniques from biomechanics. There are many examples in the literature of studies of the biology and biomechanics particularly, of human walking and running. The questions these papers answer are similar to the questions asked in studies that combine biomechanics and physiology. For example, Taylor et al. (1982) studied the energetics and mechanics of terrestrial locomotion by measuring the metabolic energy consumed and the mechanical energy changes of animals as they walked along the ground. In a later study, Biewener et al. (2004) investigated the mechanical advantage of human walking and running using an inverse dynamics approach (a typical biomechanical analysis). These authors suggested that muscle forces generated during locomotion depend on an animal's speed, gait and size and contribute to the energy demand to power locomotion. In another example of the integration of biomechanics to anthropological studies, Bramble and Liebermann (2004) reported on endurance running and the evolution of *homo* comparing humans and quadrupeds in their ability to run long distances. Lastly, an investigation of the trabecular bone in the calcaneus of runners using CT scans reported that trabecular bone thickness was associated with weekly running distance (Best et al., 2017).

Engineering

Biomechanics as a sub-discipline has become an integral area of study in both industrial and mechanical engineering. Research in these areas have focused on human walking and, as an example, studies on simulations of human walking are presented. One interesting combination of biomechanics and engineering is in the design optimization of lower limb prostheses for optimal biomechanical and clinical outcomes (Price et al., 2019). Price & Sup (2020) used computer simulations to optimize the output behaviors of a generalized prosthesis model and validate the model. A study by Chen & Posa (2021) attempted to automatically synthesize low-dimensional models that retained the capabilities of a high-dimensional system. To do this, the authors optimized their model for walking at a range of speeds and ground inclines. These few studies illustrate the influence of biomechanical analyses in the area of mechanical engineering.

Future directions

Over the last 40 years, biomechanics has become a significant research area in Physical Education and Kinesiology in addition to several other disciplines. Biomechanics has evolved from a qualitative/descriptive model of research to a highly quantitative perspective. This development to a quantitative perspective has resulted in many ways to increase in the ability to measure and evaluate movement in all areas of interest to biomechanists. The data collection and analysis techniques have led to a more detailed characterization of movement patterns. Biomechanics has become an integral area that has interfaced with several of the sub-disciplines in Kinesiology and has contributed significantly to enhancing the knowledge base in all areas. The study of the mechanical principles of movement are now employed in many disciplines external to Kinesiology leading to a wider acceptance of biomechanics as a discipline on its own rather than simply a sub-discipline of kinesiology.

However, much of the development of biomechanics has resulted from the improvement in the technology used in movement research. While just a few decades ago, a biomechanics research study would include a limited number of participants and treatments, the technology has developed such that the same study could be accomplished much quicker and probably more accurately. Much of this chapter has dealt with technological development in biomechanics but, along with the technological development, has been the development and incorporation of different analysis techniques. Biomechanics is dependent on the development of newer and faster equipment. While it may be over-reaching to say that biomechanics can solve many human movement problems, the technology has allowed researchers to at least answer more in-depth and more comprehensive questions.

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