Uniting Mathematics, Statistics, and Engineering to Help Mitigate Sports Injuries

Kristin D. Morgan

While athletic training and performance is steadily improving, sports injuries which occur during athletic activities or exercising remain a constant bane. These injuries are often due to human biomaterial and biomechanical failures that are frequently the aftermath of exceedingly high stresses experienced during cutting and high-impact movements. Such events can be catastrophic or minor. Yet, regardless of the severity, injury prevention is a major goal of sports biomechanics research. However, the lack of standardized, quantifiable metrics to define injurious biomechanics makes advancing research on mitigating injury difficult. My Human Performance Laboratory research team in the School of Engineering at the University of Connecticut has undertaken this challenge. We are focused on designing studies that best reconstruct scenarios that mirror injurious biomechanics to help develop standardized metrics to predict the likelihood of injury. Our work has been successful in integrating mathematics, statistics, and engineering tools to advance research on the critical challenges that plague sports biomechanics [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Our work is directed at identifying and tracking noninvasive metrics and tools to help enable early injury prediction and also to evaluate and accelerate an individual's return to sport after an injury. Thus, the following discussion will highlight the implementation of autoregressive (AR) modeling, bootstrapping, logistic regression, and neuromuscular and musculoskeletal modeling in OpenSim, a free open-source musculoskeletal software system used to investigate musculoskeletal dynamics during movement, to help characterize and mitigate sports injuries due to injurious biomechanics.

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Characterizing Injurious Biomechanics via Autoregressive Modeling

The human body generates numerous biomechanical signals related to motion and displacement. Injurious biomechanics occur when individuals perform outside of their "normal" operating ranges. Although previous studies have revealed there is indeed some variability in these signals in healthy individuals, an analysis of physiological signals (e.g., cardiac and respiratory signals) has uncovered that adverse cardiac and respiratory events can be detected from abnormal signal variability [11, 12]. This work was significant in highlighting that it was not solely the magnitude of the signal but a change in the underlying signal structure variability that often precedes adverse events [4, 5, 7]. Building on this work, my team has designed a gait perturbation study to safely destabilize individuals while walking [5]. Second-order AR models fit to the stride time data captured under three different gait test protocols were successful in classifying the healthy and unhealthy individuals [5]. Such second-order AR models best capture the underlying second-order processes of human movement that are governed by the equations of motion. These second-order dynamics were confirmed via the analysis of the structure of the autocorrelation and partial autocorrelation functions that revealed a dominant second-order pattern in the stride time data [13]. An added benefit of this AR model was that we could exploit the graphical features of the models to track and visualize how individuals transitioned between low and high gait instability regions associated with potential injury. Gait instability is often an early indicator of other impending medical conditions. Therefore, we have also explored the use of AR modeling to characterize both injury risk and cognitive dysfunction. In our future work, the AR modeling methods developed to characterize injury risk may also be beneficial in fostering the early detection of neurodegenerative disorders (e.g., Huntington's and Parkinson diseases) which then leads to early intervention and thereby could help slow disease progression [4]. Hence, our long-term research goals extend beyond sports injuries to other diverse populations.

Utilizing Bootstrapping to Overcome Small Sample Sizes

Small sample sizes in the era of big data seems contradictory; however, it is important to distinguish between large amounts of data and meaningful data. While wearable devices are valuable for collecting biomechanical data outside of the laboratory, their limited in-game use when injuries tend to occur have, to date, not resulted in a significant increase in biomechanical injury data. Thus, we are reliant on studies that can simulate a variety of injury scenarios without actually inducing an injury. However, even in these well-designed studies, sample sizes often range from 20 to 40 individuals resulting in broad generalizations about injurious biomechanics. Yet, bootstrapping serves to enhance the predictive capability of small, restrictive datasets [14]. Bootstrapping is a resampling routine that improves data efficacy by simulating replicate data sets of the original data to estimate the sampling variability and other distributional properties [14]. We have integrated this technique in our AR modeling approach to magnify the underlying gait dynamics associated with individuals with an anterior cruciate ligament (ACL) injury [10]. The bootstrapping technique was critical in improving the delineation between the injured and healthy populations and it led to a rapid classification of an individuals' potential injury risk. Hence, the approach is cost-effective because you get the benefits of big data without running a large number of trials. Future work will expand this methodology to evaluate movement dynamics related to knee patellofemoral pain and stress fractures.

Employing Novel Metrics and Logistic Regression to Define the Likelihood of Injury

Advanced data analytics are essential to much of what we do in sports biomechanics since it allows us to describe, diagnose, and predict altered biomechanics from movement data. Machine learning is at the forefront of these data-driven analyses; however, the performance of machine learning models is dependent on the strength of the input metrics. Thus, my laboratory has made a concerted effort to develop novel, standardized metrics that provide universal ranges and/or thresholds to denote injurious biomechanics [3, 6]. These metrics include a peak force to loading rate ratio that functions as an index for assessing healthy motor control. More recently, we have developed a model that connects muscle torque production and rotational energy expenditure. The results yield two dimensionless variables that map torque production to injury frequency. To optimize the effectiveness of these metrics, we developed a logistic regression model to predict the probability of injury as a function of this metric. This allows us to establish ranges of injury risk likelihood that are important for the early detection and the implementation of early intervention measures that can dramatically decrease injury rates.

Future Directions

To successfully mitigate sports injuries will require interdisciplinary, new approaches that incorporate mathematics, statistics, and engineering. It is unquestionable the impact mathematics and statistics have had on the field of sports biomechanics engineering research. To maximize the impact of this work, our goal is to transition this work from the laboratory to healthcare professions, clinicians, and individuals. Our long-term research vision is to uncover easily captured noninvasive metrics and develop personalized biometric algorithms to be embedded into sensors, wearable devices, and apps to alert the user of declines in their biomechanics in advance of potential sports injuries. This will provide users with wearable, clinical-based diagnostic capabilities to bolster injury prediction. The success of this goal ultimately hinges upon the combined efforts of (1) constructing novel noninvasive metrics to aid the early prediction and rapid diagnoses of injury biomechanics; (2) developing subject-specific models for movement optimization using the OpenSim engineering modeling and simulation of movement software (`https://simtk.org/`); and (3) designing innovative intervention protocols.

In summary, the proposed work converges at the intersection of mathematics, statistics, and engineering and fosters the development of novel biomedical engineering tools to help optimize the health and performance of individuals. Additional detailed information about this research is available in the referenced articles and the Data & Science with Glen Colopy Podcast (May 10, 2021) [15].

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