Towards the Development of a System Dynamics Model for the Prediction of Lower Extremity Injuries

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ABSTRACT

International Journal of Exercise Science 16(3): 1052-1065, 2023. Acute noncontact Lower Extremity (LE) injuries constitute a significant problem in team sports. Despite extensive research, current knowledge on the risk factors of LE injuries is limited to static simplistic models of instantaneous cause and effect relationships ignoring the time dimension and the embedded complexity of LE injuries. Even though complex systems approaches have been used in various cases to improve policy and intervention effectiveness, there is limited research on predicting and managing LE injuries. This creates an opportunity to fill the gap in the current literature by applying the System Dynamics (SD) methodology to model LE injuries. The proposed approach allows for synthesizing risk factors and examining their interaction. This paper makes the first step towards such an approach by developing a causal loop model revealing the etiology of LE injuries. A causal loop model for LE injuries is developed via an extensive literature review and brainstorming with experts. In contrast to the traditional static approaches, the proposed model reveals some of the complexity and nonlinear relationships of the various sports injury risk factors. The derived causal loop model may then be used to quantify these interactions and develop a simulation model. This will be achieved by operationalizing and incorporating the main risk factors that impact LE injuries in an integrated sports injury prediction model. In this way, plausible strategies for preventing LE injuries can be tested prior implementation and thereby achieve optimization of intervention programs.

KEY WORDS: Complex systems, system dynamics, sports injury prevention, noncontact lower extremity injuries, team management

INTRODUCTION

Acute noncontact lower extremity (LE) injuries cause a significant absence from training and high competition, leading to long-term negative consequences on the athlete’s overall health (26, 48) and performance (14). Therefore, it is crucial for the sports health science team to better understand, predict, and prevent sports injuries. The traditional process of investigating sports
injuries follows a reductionist approach, in which the complex mechanism of sports injury is separated into parts and analyzed (40). Such examples of simplified linear models can be identified in studies that assess the impact of muscle strength asymmetries and imbalances in acute muscle injury (5) or the connection of the knee valgus with the Anterior Cruciate Ligament (ACL) injury (25).

Although this approach is beneficial because it provides evidence about the linear connections of some risk factors with an injury, it fails to adequately represent the whole picture of the nonlinear interactions among the sports injury risk factors and to synthesize them in a concise model (40). The sports injury etiology has recently been characterized as a dynamic and complex phenomenon (7, 17). This means that many interacting factors are spontaneously organized and adjust or generate new properties in response to perturbations. The factors’ interaction creates self-organized systems (7, 17). These factors exchange information with their environment as open systems (7), producing dynamic adaptations of their properties over time. For instance, the complex interrelationships among physiological and psychological factors represent a web of determinants that rapidly change its form to respond to the athlete’s environment (44). The change in a factor affects the determinants’ interaction producing an nonlinear unexpected system’s response (7, 44).

Understanding the complexity of sports injuries might allow better recognition of regularities in injury etiology. Bittencourt et al. (7) report that the factors’ interaction into a web of determinants produces either a protective or a high injury risk profile. Specifically, regarding ACL injury, determinants that seem to interact nonlinearly include training load, abductor weakness, knee valgus, fatigue, sex, and previous injury (7). The evidence mentioned above highlights the need to approach the problem from a nonlinear System Dynamics (SD) perspective (28). The utilization of complex systems computational methods in the sports injury field provide valid insight into injury etiology and, consequently, a more effective injury prediction (28).

Different dynamic injury models have been reported (4, 34, 47) in the literature focusing on sports injury etiology. Even though some researchers have proposed using the SD modeling method, it has not yet been applied to sports injury research (28). Recently, many studies have used computational modeling methods and algorithms to simulate the complex nature of sports injury. These methods include machine learning algorithms (41) and Agent-Based modeling (30). López-Valenciano et al. (32) showed that a machine learning algorithm had a moderate predicting ability to determine if athletes are at high risk of muscle injuries in team sports. Factors that significantly contributed to the injury risk profile included the athlete’s devaluation of the expected benefits of participating in sports, previous musculoskeletal injuries, and isokinetic knee characteristics (32). The study (32) concluded that machine learning algorithms could effectively replace traditional statistical methods and help health and sports scientists in the decision-making process for injury prevention. Alternatively, Ruddy et al. (41) assessed the predictive ability of future hamstring injuries using a machine-learning modeling method. The model examines the interrelationship of demographic data, age, previous injury, and eccentric
hamstring strength, showing a moderate to low predictive value (41). Further, Hulme et al. (30) use an agent-based modeling approach to simulate the dynamic relationship between acute-chronic workload ratio and long-distance running injuries. This study (30) follows a previous static framework for running-related injuries (29). Besides the difficulties, some studies (29, 30) concluded that further research is necessary to improve the use of complex systems modeling methods in sports injury prevention.

As a result, SD modeling represents a popular method to simulate complex systems, and its application to health-related research has been rapidly increasing over the last few years. There have been successful SD applications in the topics of obesity, diabetes, cancer, cardiovascular, and other chronic diseases (10, 11). Researchers have applied SD simulation modeling approaches at the population, group, or individual levels (10). These models were used to understand the function of complex health problems and examine the effect of different interventions. Their scope is to capture either the flow of patients among the different phases of a health problem or the patient’s level of progress with respect to disease (10). An example of the above is the implementation of SD for the control of short-term blood pressure via a simulation model of the function of the cardiovascular system. Thereby, researchers assessed physiological and pathological conditions such as stenosis or edema. All factors that impacted blood pressure were used to form feedback loops using Causal Loop Diagrams (16).

The theoretical background and advantages of utilizing the SD modeling method in sports injury have recently gained significant interest. However, to the authors’ knowledge, no study has been conducted using SD modeling to investigate the complex and dynamic nature of interaction among the factors contributing to LE sports injury. This paper firstly aims to present the different components of SD modeling and the methodology of formulating such a model. Further, this paper aims to develop a theoretical causal loop model, using literature evidence on LE injury risk factors, as an attempt to capture the complex nature of such injuries. This paper is organized into three main sections to facilitate the understanding of our modeling approach. Specifically, the first section presents information regarding system dynamics modeling. We separate this section into two parts, including the description of the causal loop, stocks and flows diagrams, and the group modeling building. In addition, the second part presents the implementing causal loop model, and in the last part, we discuss the present attempt for LE sports injuries modeling.

SYSTEM DYNAMICS (SD) MODELING

The SD method is one of the most popular computational techniques. Previous studies have used SD modeling to examine complex health problems (10). This method examines the factors’ nonlinear interactions in the system under consideration. Additionally, it predicts the system’s function and the movement of the quantities in the system over time (9, 28). For this purpose, an SD model uses differential equations to present changes in the variables of interest. The dynamic components of the SD model are feedback loops, stocks, and flows (43).
Causal loop, stocks and flows diagrams
The SD method's crucial initial phase is forming causal loop diagrams. These represent the system’s structure and include all the factors and variables that affect the system’s function (9, 28, 43). Furthermore, causal loop diagrams consist of many feedback loops, which are the basic components for SD modeling. In feedback loops, each factor is connected with others with links, shown by arrows, representing the associations and the causal influence among the variables. The crucial feedback loops in an example of the causal loop model are highlighted in Figure 1 (43). Each link has a specific polarity, positive or reinforcing (+) and negative or balancing (-). The polarities show how the dependent variable behaves when the independent variable changes (9, 28, 43). In the case of a positive or reinforcing link, when the independent variable increases, the dependent variable also increases, and vice versa. On the other hand, in the case of a negative or balancing link, when the independent variable has increased, the dependent decreases, or when the independent variable has decreased, the dependent increases (43).

For instance, declining an athlete’s biomechanical characteristics can increase the injury risk. At the same time, the injury would cause negative adaptations to biomechanical properties. This association represents a reinforcing feedback loop. On the other hand, a high workload can lead to an injury, but the workload would be decreased due to the athlete’s absence from practice or games. The above association represents a balancing feedback loop (see Figure 1).

![Figure 1. Multiple causalities for sports injuries](image)

Link polarity indicates whether there will be an increase or decrease in the variables shown in Figure 1. It does not exactly represent the action of a variable but what would happen in the case of a variable change. Link polarity captures the formation of the system (43). Additionally, many other factors may affect a variable in the system. We need to know all the variable's inputs and polarities to define what happens. Every other variable in a feedback loop interacts with other elements and represents a segment of the whole causal loop diagram (43).

Further to the causal loop diagram, the stock and flow model presents the accumulations of quantities and the rate of changes in these quantities (43). Stocks are accumulations of quantities, and flows represent the rate of the movement of those quantities. Flows add (inflows) or remove (outflows) quantities from the stocks. The causal loops affect the accumulations of the quantities.
and the function of stocks and flows diagram (43). For instance, due to the interactions among the injury risk factors presented in the causal loop diagram, the stocks and flows diagram represents the movement of athletes from the healthy state to the predisposition to the injury state. In that way, the model simulates the system’s function and can make predictions of athletes’ likelihood of injury. Hulme et al. (28) formulated an SD model regarding running injuries, including stocks and flows diagram and causal relationships among factors. The model’s function predicts the likelihood of running injuries.

**Group Modeling Building**

Group modeling building is the method for creating the causal loop diagram and the overall system dynamics modeling (6, 42). Group modeling is a cooperative process that includes experts in the field of the examined issue and stakeholders. Specifically, expertise is necessary for sports injury and system dynamics modeling. Moreover, the community members where the problem arises are equally important for the process. These members can be sports physiotherapists, sports scientists, doctors, coaches, trainers, or other members who are connected with the athletes and the field in which the problem of injury arises (42). The process includes performing several scripting exercises structured in sessions of group modeling workshops. The output of this process is the formulation of an optical display of the issue examined via the SD model (42). This procedure of group modeling building promotes an in-depth and complete understanding of the system’s operation under consideration and guides the actions that may need to be taken (6, 42).

The Group modeling building incorporates the five steps needed for the final formulation of the SD model, as shown in Table 1 (43). Steps 1-2 include a qualitative process. These steps concern defining the problem, considering the critical variables (43), and formulating a causal loop model with subsystem diagrams that explain the system’s dynamics. Steps 3-5 are more quantitative. These steps involve developing the simulation model by incorporating the stock and flow diagrams into the causal loop, testing the model’s cohesion, and evaluating different scenarios (42).

<table>
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<th>Table 1. Steps for the formulation of SD model</th>
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**IMPLEMENTING SYSTEM DYNAMICS MODELING METHODOLOGY**

This section analyzes the issue of acute noncontact LE injuries via causal loop modeling, which is the first step in formulating a simulation SD model. Figure 2 shows a theoretical example of a
causal loop diagram. Based on previously proposed models (7, 34), literature review, and experts’ opinions, the proposed diagram attempts to present a holistic view of the complexity and nonlinear interactions among injury risk factors. More precisely, we search the databases of Scopus and PubMed for the main risk factors and computational modeling. For that purpose, we used a combination of the keywords "lower limb", "lower extremity", "injury", "noncontact", "acute", "injury prediction", "complex systems", "system dynamics", "computational modeling", "simulation". Then, we perform two workshops to develop the causal loop diagram. In this process, we incorporated three experts from a physical therapy education institute specializing in sports injury rehabilitation, two sports clinical physical therapists, and an expert in SD modeling. In order to create a causal loop diagram that would present a more comprehensive and realistic view of the problem, we included the opinions of the modeling team mentioned above in accordance with the literature evidence. We use the Vensim software (Ventana Systems Inc, Harvard, MA) to formulate the causal loop diagram.

The model presented in this paper incorporates the first and a part of the second qualitative step of the five steps needed in the process of the entire application of SD methodology in sports injuries (Table 1). In these initial steps, the causal loop diagram incorporates the perspectives of the core modeling team. Steps following this initial work should embody multiple stakeholders, using structural group modeling workshops, in order to include in the final SD model elements of their point of view (6, 42). The main stakeholders may be athletes, trainers, and sports scientists. In this way, this simplified causal loop diagram may be further modified to be more specific to each LE injury and improved to contain the influence of larger social, health care, economic, and technological systems. The model shows a perspective of factors’ nonlinear association. The connections between elements have either a positive effect (+), or a negative effect (-), and the links create loops that are characterized either as reinforcing (R) or balancing (B).

Risk factors are traditionally divided into intrinsic (or internal) and extrinsic (or external) that represent the athlete-related factors and the environmental or equipment factors, respectively (4). However, the elements in the various categories do not act independently but collectively contribute to the complicated etiology of injury (7). As presented in the R1 feedback loop of Figure 2, an intrinsic risk profile takes athletes in a predisposition state. Then predisposed athletes are exposed to training and competitions that interact with extrinsic risk factors, making them susceptible to injury (34). Consequently, the susceptible athlete is exposed to risk for injury with a probability that an acute noncontact LE injury will happen (34). Injury occurrence depends on factors such as athlete susceptibility and exposure rate to the risk of injury over time.

The risk of injury is further increased by risk situations during the game (B4 feedback loop of Figure 2), such as the athlete’s involvement in sprinting, landing, aggressiveness, and directional movement (7, 34, 47). An athlete’s high-quality movement is critical to cope with these demanding situations. Regarding that, neuromuscular and appropriate movement quality reduce the predisposition for injury and, as a result, reduce the susceptibility when the athlete interacts with external risk factors (B1 feedback loop, Figure 2). Therefore, movement
biomechanics seems to be of great interest in the literature since impairments in specific motions have been associated with various acute LE injuries (1, 26). Specifically, biomechanics of landing and cutting maneuvers have been linked with ACL (1, 26) and ankle injuries (23). Similarly, muscle activation patterns and kinematics variables during sprinting have been studied for hamstring strain injuries (39).

Figure 2. A Causal Loop Diagram example of Risk factors interactions and complexity for acute noncontact LE injuries. B and R with circular arrows represent the balancing and reinforcing feedback loops, respectively. Green arrows represent the internal and red arrows the external risk factors.

Further, psychological quality is affected by previous injury and the biomechanical – neuromuscular quality. This association is highlighted in the B2 and B3 feedback loops of Figure 3. The literature mentions that team sports athletes who have experienced a recent adverse event in their life, such as a death in their family, have increased stress and anxiety (19). These psychological symptoms may result in higher muscle tension and decreased athlete concentration during the game, increasing the risk of an acute injury (12, 32). As a result, the athlete’s psychological condition affects exposure to situations during the game that increases the injury risk (B2 feedback loop, Figure 3) (12, 32).

When a new injury happens, after a period of rehabilitation, these athletes will reenter the cycle of predisposition, susceptibility, and exposure to injury risk. The diagram (Figure 3) expresses the rehabilitation period with a time delay (two parallel lines between the rehabilitation rate and predisposed athlete). The injury and the rapid interaction of the athlete with extrinsic factors may cause dynamic modifications in the quality of the athlete’s intrinsic modifiable characteristics (17). Figure 4 clarifies this association, as the quality of movement is affected not
only by intrinsic biomechanical quality but also by extrinsic factors. As a result, an improperly integrated rehabilitation program, the inactivity and the time-loss for participation in athletic activities after an injury promote adaptations to modifiable factors such as atrophy, muscle strength imbalances, a decline in core stability, and electromyographical time delay (20, 22, 26, 39, 46, 48). These modifications will create a new intrinsic risk profile.

![Figure 3. Feedback loops creating due to injury.](image)

Consequently, based on the associations presented in Figures 3 and 4, the degree that the previous injury contributes to the risk profile depends on the modification strategies to improve the athlete's neuromuscular characteristics such as eccentric muscle strength, balance, muscle activation pattern, sense of effort, and force (39). Additionally, adequate modifications on workload, rate of play, and training would be beneficial for at-risk athletes. Sports teams should incorporate specific prevention strategies for athletes with previous injuries (39). Therefore, the coach’s decisions for sports participation and cooperation with athletes and medical staff are of great importance (15). Specifically, Figure 2 clarifies that coach decisions may impact the athlete’s workload, exposure rate, and exposure to risk situations during the game. These are critical factors regarding injury occurrence, especially for predisposed athletes. Hence, high quality of communication among medical and training staff is vital for injury prevention (15).

In addition to the above, another significant nonlinear influence comes from the workload that positively affects fatigue (47). The workload influences the athlete’s cardiorespiratory and muscle endurance, which affects an athlete’s ability to cope with fatigue (47). Subsequently, fatigue impacts the biomechanical risk parameters, making an athlete more prone to high-risk movement biomechanics (45), as shown in Figure 2. On the other hand, when the workload is at the desired level, without spikes between the acute and chronic workload, it causes positive modifications to athletes' physiological characteristics, preventing them from injuries (2, 8, 21, 36).
The intrinsic and extrinsic risk factors do not act independently but interact dynamically. The complex mechanism of injury arises from the ability of each risk factor to interact nonlinearly and cause alterations in other factors (7, 27, 40). For instance, a high-friction surface and shoes with high-friction properties lead to a shoe-surface high-friction interaction. This association seems to impact lower extremity biomechanics components that may increase the risk for injury (13, 33, 38). Moreover, climatic conditions may affect this interaction as they are associated with playing surface conditions and shoe-surface friction (37). Moreover, the athlete’s neurocognition function seems to contribute to the quality of movement. Various neurocognitive skills have been linked with an athlete’s capability to process information and make decisions for action during challenging circumstances during the game (18). Regarding that, athletes’ decreased performance in neurocognitive characteristics such as visual-spatial memory, visual attention, and processing speed/reaction time could produce kinematic and kinetic patterns that increase the risk for ACL injury (24, 35). Consequently, as shown in Figure 4, an influence framework of different intrinsic and extrinsic factors affects the overall quality of movement (7, 34).
DISCUSSION

This paper describes the complex nature of acute noncontact LE injuries. The great variety of risk factors indicates that the etiology of acute noncontact LE injuries is highly complex. This creates the need for an appropriate approach, such as the SD method, which is deemed suitable for analyzing complex systems. After a comprehensive literature review and experts' opinions, the most important intrinsic and extrinsic risk factors are derived, and a causal loop model for the etiology of acute noncontact LE injuries is proposed.

Similar to our approach, Bittencourt et al. (7) introduced the concept of complex systems in sports injury etiology and the model presented in this paper is based on the same theoretical background. Based on the conceptual approach of Bittencourts et al. (7) and reinforcing the understanding of the complex sports injury phenomena, we proposed, as a step forward, a simulation system dynamics model using a causal loop diagram as a part of this methodology. The causal loop diagram presented here constitutes a first attempt to capture acute noncontact injuries’ dynamic and complex etiology. This diagram captures the interaction among the risk factors and provides a qualitative but comprehensive view of the complex etiology of acute noncontact LE injuries. The causal loop model highlights that a change in a variable produces positive or negative changes in other interacting factors. Finally, this change will affect the whole system of the injury etiology resulting in a specific risk profile (7).

The current practice of dealing with injuries includes a pre-season screening of risk factors, followed by athletes' monitoring to record injuries. Finally, injuries are associated linearly with the factors that have been evaluated (3). This procedure ignores the dynamic ability of modifiable factors to change over time and the interrelationships among factors. Athletes' injury profile in the pre-season screening may be altered during the season or when the injury occurs because of the interaction of intrinsic modifiable factors with extrinsic factors (7). These isolated associations should then undergo a synthesis process to improve prediction. The system dynamics approach is the most suitable method for integrating these interrelationships (7).

SD method can illustrate these nonlinear interactions among risk factors and makes it possible to see changes over time. This allows researchers to improve their beliefs about the system’s function and enhance their understanding of the etiology of acute noncontact LE injuries. Also, it provides the ability to simulate and examine the effect of different interventions in injury prevention programs (27, 28). Consequently, SD can help with injury prediction and prevention (3). The ability of SD to capture the dynamic interactions among a system's factors differentiates it from other more static complex systems methods such as machine learning (28). Machine learning approaches are described before (32, 41) as an attempt to model the interaction of injury risk factors. However, these models have a moderate predictive ability. Different mathematical algorithms and machine learning are useful for analyzing aspects of complex systems at specific time points and across different levels. In contrast, SD modeling can simulate the system's function and the dynamic adaptation to the injury risk factors over time, making the prediction possible (28).
Further, the adjacent methodology of group modeling building provides the opportunity to include main stakeholders in the modeling process for an in-depth understanding of the problem situation of acute noncontact LE injuries (42). This process leads to the formulation of a comprehensive causal loop diagram. It is important to mention that the causal loop diagram is a crucial section of SD modeling and illustrates the influences of different factors (31). However, to have the quantified dynamics of a system, an SD simulation model is necessary (31).

As shown in this paper, the formulated causal loop model provided us with a shared, clearer view of the complex etiology of acute noncontact LE injuries. However, the model proposed here has various limitations. First, the entire methodology of group modeling building was not totally applied. The application of this method engages experts and multiple stakeholders, such as sports medical experts, sports scientists, sports physiotherapists, and coaches, in numerous organized workshops to formulate a comprehensive and valid model. The entire application of this methodology is beyond the scope of this paper and is the aim of further work. This paper’s primary purpose is to review the main components of SD methodology. The formulated causal loop model integrates the first and a part of the second step toward developing an SD simulation model. Second, this model considers all acute noncontact LE injuries ignoring the different risk factors and interactions that may arise in specific injuries, such as hamstring strains and ACL injuries. For that purpose, more specific models should be created. Finally, the model is a qualitative perception of the multiple interactions among the factors, and the quantification of these interactions will be necessary for future studies.

In conclusion, a more comprehensive and specific to each injury causal loop models with subsystem diagrams, the quantification of these interactions, and an SD simulation model based on the methodology employing a group modeling technique are planned for future studies. This will provide the ability to better understand the etiology of injury and predict the likelihood of an injury after considering the main stakeholders’ views. Moreover, an SD simulation model can enhance the existing injury prevention programs, as it provides the opportunity to test plausible interventions.

REFERENCES


