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1 **An Ecological Dynamics Approach to ACL Injury Risk Research: A Current Opinion**

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24 **Abstract**

25 Research of non-contact anterior cruciate ligament (ACL) injury risk aims to identify modifiable risk factors that
26 are linked to the mechanisms of injury. Information from these studies is then used in the development of injury
27 prevention programmes. However, ACL injury risk research often leans towards methods with three limitations:
28 1) a poor preservation of the athlete-environment relationship that limits the generalisability of results, 2) the use
29 of a strictly biomechanical approach to injury causation that is incomplete for the description of injury mechanisms,
30 3) and a reductionist analysis that neglects profound information regarding human movement. This current opinion
31 proposes three principles from an ecological dynamics perspective that address these limitations. First, it is argued
32 that, to improve the generalisability of findings, research requires a well-preserved athlete-environment
33 relationship. Second, the merit of including behaviour and the playing situation in the model of injury causation is
34 presented. Third, this paper advocates that research benefits from conducting non-reductionist analysis (i.e. more
35 holistic) that provides profound information regarding human movement. Together, these principles facilitate an
36 ecological dynamics approach to injury risk research that helps to expand our understanding of injury mechanisms
37 and thus contributes to the development of preventative measures.

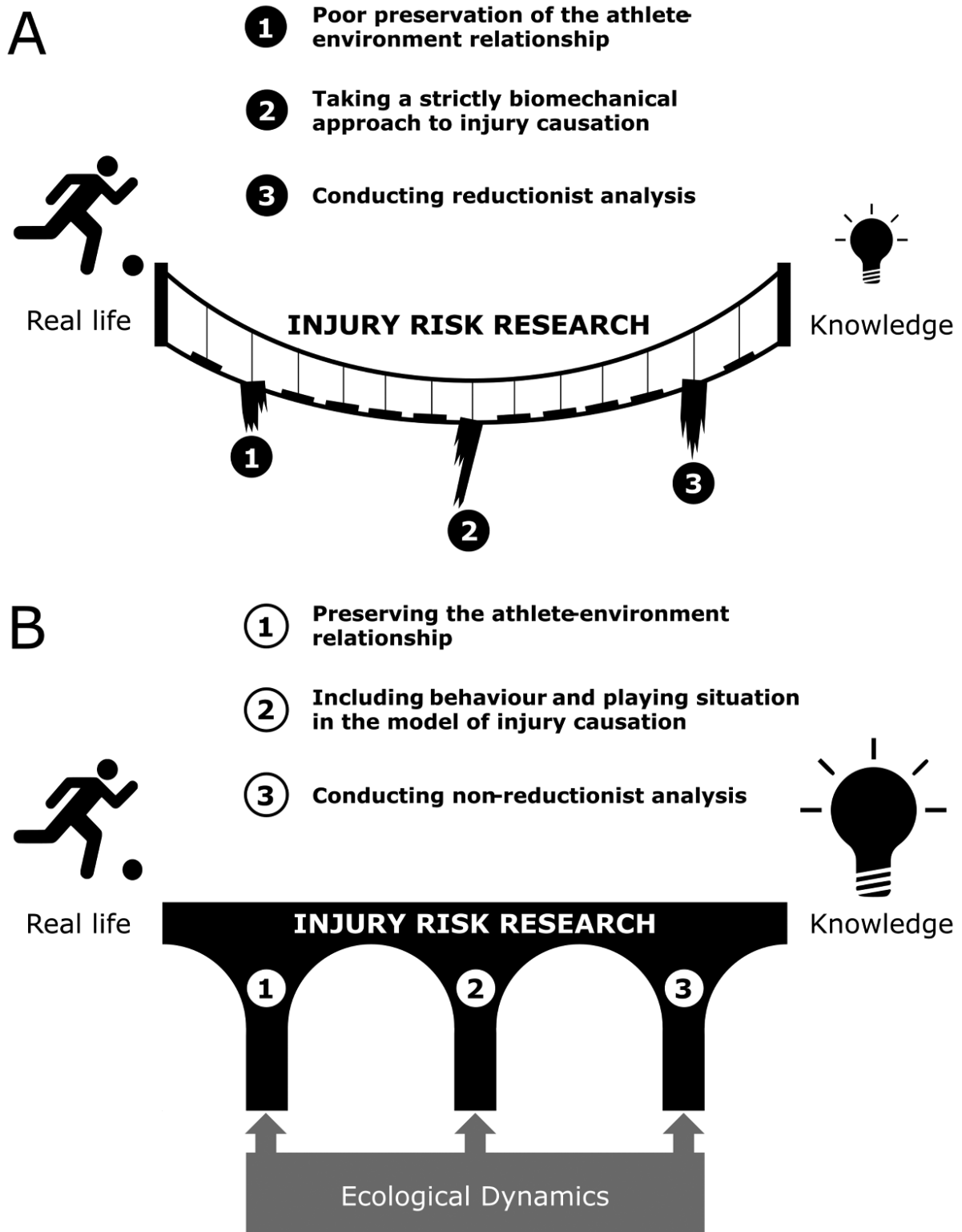
38 **Keywords:** Ecological Dynamics, ACL, Injury risk research, Non-reductionist, Self-organisation

40 Non-contact anterior cruciate ligament (ACL) ruptures are injuries that typically occur during dynamic movements
41 such as rapid deceleration or change of direction [1]. These injuries involve significant financial costs for society,
42 large personal burden due to the great number of days of absence from training and match play [2, 3], and a high
43 risk of post-traumatic osteoarthritis [4]. Due to these long-lasting consequences, the prevention of ACL injuries
44 should have top priority [5]. Over the past 20 years, researchers have identified modifiable (biomechanical and
45 neuromuscular) risk factors related to the mechanisms of ACL injury in team sports [e.g. 6–9]. These risk factors
46 have provided information for the development of ACL injury prevention measures [5], through the ‘Sequence of
47 Prevention’ model [10]: i.e., 1) establishing the extent of the sports injury problem (incidence & severity), 2)
48 establishing aetiology and mechanism of injuries, 3) introducing preventive measures, and 4) assessing their
49 effectiveness by repeating step 1.

50 Establishing the modifiable risk factors and mechanisms of injury through injury risk research is an essential step
51 in the ‘Sequence of Prevention’[10]. These lab-based studies typically aim to mimic movements in that
52 characterize injury risk scenarios such as change-of-directions or jump landings and assess the biomechanics
53 associated with these movement tasks [11]. Considering the importance of these injury risk studies, we have the
54 following concerns regarding their methods. First, injury risk research typically takes place in a laboratory setting
55 that fails to preserve the athlete-environment relationship. As a result, the generalisability of findings may be
56 limited. Second, injury risk research is often conducted from a strictly biomechanical approach. This is
57 representative of adopting a ‘narrow’ model of injury causation, as this approach may overlook the effects of other
58 variables, such as player behaviour or the surrounding environment. Third, injury risk studies that analyse single-
59 joint biomechanics using linear statistical measures are reductionist and neglect information about the adaptability
60 and complexity of human movement. Together, these aspects of injury risk research methods limit the knowledge
61 gained from these studies and thus narrow our understanding of injury risk (Figure 1A).

62 To address these limitations, we propose an approach from an ‘ecological dynamics’ perspective that considers
63 the human body as a complex adaptive system that interacts with its environment, which is best studied at the
64 athlete-environment level of analysis [12]. Although this ecological dynamics perspective is already prominent in
65 the fields of sports performance [13–15] and sport psychology [12, 16, 17], its implementation in injury risk
66 research is limited. While this paper specifically discusses non-contact ACL injury risk research, this approach is
67 also applicable to other domains. This article consists of three parts. First, we describe how movements emerge

68 through self-organisation and underline the importance of 'context' in studying movement behaviour and its
69 relation to injury situations. Second, we discuss three principles that enhance ACL injury risk research (Figure
70 1B): preserving the athlete-environment relationship, including behaviour and the playing situation in the injury
71 causation model, and conducting non-reductionist (i.e. more holistic) analysis. Finally, we conclude with an
72 example of a study design that adheres to the proposed principles. By providing these principles, we hope to offer
73 researchers an approach that helps expand the understanding of injury mechanisms and thus contributes to the
74 development of effective preventive measures.

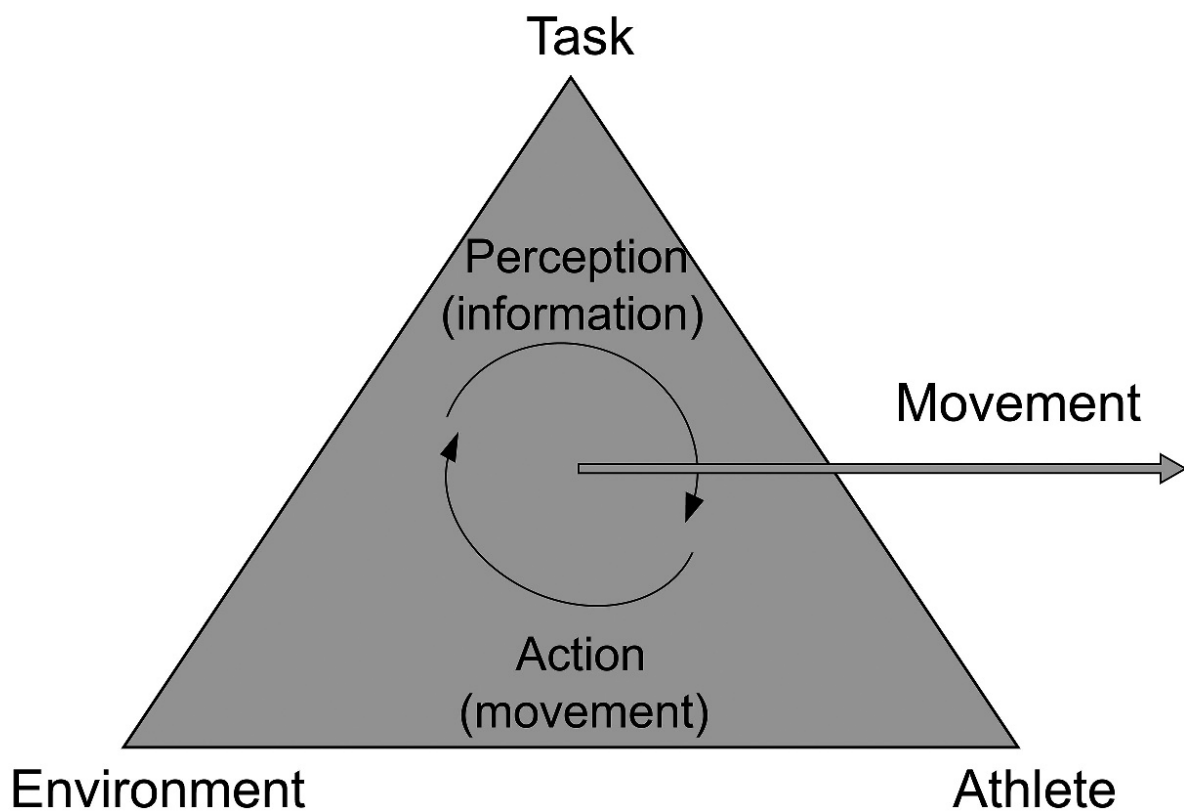


75

76 **Figure 1.** Schematic representation of injury risk research as the bridge between *real life* and *knowledge*. A)
 77 Limitations of current injury risk research methods are pitfalls that limit the knowledge obtained from these studies.
 78 B) Principles for an ecological dynamics approach to injury risk research. These principles provide a foundation
 79 for research that is more generalizable and less reductionist, expanding the knowledge that is obtained.

80 2 'Context' and self-organised movements

81 Human movement can be viewed as the emergent result of the interaction between the athlete and its surrounding
82 context [18]. The athlete performs in a context that is shaped by three types of constraints; the individual
83 constraints, the environmental constraints, and the task constraints (Figure 2). Individual-related constraints, for
84 example, may concern the athlete's characteristics such as height, weight, limb length, fatigue, or anxiety [19].
85 Environmental constraints may include features like the type of terrain, light condition, weather, or boundaries of
86 the field. Task constraints may include the goal of the task and any rules or objects that specify or constrain the
87 athlete's response dynamics, for instance the actions of other players [19]. Together, these constraints shape the
88 context in which the athlete perceives and acts. Movement in sport is therefore not produced by an isolated athlete,
89 but emerges from a dynamically varying coupling between the athlete's characteristics, the stimulus-rich
90 environment, and the desired actions (i.e. tasks) [20].



91

92 **Figure 2.** Movement is the emergent result of the athlete perceiving and acting within a context that is shaped by
93 its constraints [18]. An adapted figure from Davids et al. [21].

94 Adopting this view of movement behaviour has two important consequences for studying movement. First, most
95 constraints are changeable and in fact may change rapidly (e.g. the relative position of players, fatigue levels, ball
96 possession). Second, the relationship between the produced movement and the underlying constraints is nonlinear.
97 To clarify, small changes to individual, task or environmental constraints can cause dramatic changes in movement
98 patterns [19]. Additionally, changes in different types of constraints can result in the exact same effect on the
99 movement pattern [22]. Recognising the changeable nature of constraints and the nonlinear relationship between
100 constraints and movement is essential in studying movement behaviour.

101 In the process of self-organised movements, perception and action are coupled and cannot be studied in isolation.
102 Expert athletes are not solely proficient movers, but excel in perceiving information from the environment and
103 execute actions accordingly [16, 23, 24]. This direct connection between movement and the environment warrants
104 research at the athlete-environment level. Therefore, if experimental studies intend to investigate game-like
105 movement behaviour of athletes, aiming to preserve the athlete-environment coupling by adding game-specific
106 stimuli is essential to elicit generalizable movement patterns [25].

107 **3 Principles for an ecological dynamics approach**

108 **3.1 Preserving the athlete-environment relationship**

109 Athletes in team sports have to quickly perceive not only their own action opportunities but also those of opponents
110 and teammates, while performing a movement. These continuous actions are performed under time pressure as
111 movement possibilities emerge and disappear. A non-contact injury is therefore the result of a series of self-
112 organised movements that emerge from the interaction with quickly changing constraints. Video analysis has
113 shown that non-contact ACL injuries in team sports typically occur when the athlete is in close proximity to an
114 opponent, while the athlete or the opponent is in possession of the ball [26–28]. To acquire generalizable
115 information about risk factors and injury mechanisms in these scenarios, experimental research should strive to
116 present athletes with game-like variables so that the elicited movement is more reflective of the movements in
117 injury scenarios.

118 Traditionally, the laboratory-based injury risk studies inherently provide athletes with limited room for self-
119 organisation of their movements. Athletes are usually instructed to move along a predefined trajectory at a certain
120 speed or to perform a jump in a marked area. Generally, game-like variables, such as interactions between
121 participants or between the athletes and a ball, are omitted to preserve the standardisation and the repeatability of
122 the protocol. Instead, participants are often instructed to respond to a simple visual cue that is atypical of the

123 complex visual stimuli in game situations (e.g. an LED lighting up or an arrow being displayed) [29]. Furthermore,
124 trials wherein the participant fails to successfully complete the prescribed task are typically discarded. As a
125 consequence, the movement tasks studied in the lab are different from the movement behaviour that would emerge
126 from scenarios on the pitch [25]. The poor generalisability of these studies limits a critical step of the ‘Sequence
127 of Prevention’ model; to identify risk factors and injury mechanisms[10].

128 In the last decade, researchers have made efforts to include game-like variables into their experiments. For
129 instance, some studies have included sport-specific dual-tasks like dribbling, intercepting, or passing a ball during
130 a change-of-direction manoeuvre [30–33]. Other studies had the athlete respond to an opponent or a video
131 projection of an opponent in a simulated game scenario [34–37]. In addition to this, rather than discarding
132 unsuccessful trials, some studies have investigated the underlying coordination of unsuccessful task performance
133 [38] or used the number of unsuccessful trials as a performance measure [24]. These improvements in methods
134 are commendable and exemplary steps towards the first principle: preserving the athlete-environment relationship.
135 However, researchers should remain careful when generalising findings from these studies. Studies should first
136 specify the context toward which they intend to generalise their findings, and then explain how that context is
137 represented in their experimental designs [39].

138 Researchers that wish to adhere to this principle should consider designing experiments which maintain the athlete-
139 environment coupling by including elements of the sport that are relevant to the game scenario of interest; such as
140 the ball, other players, and objectives that are related to real game scenarios (e.g. evading, intercepting). Of course,
141 such experiments are best performed on the field. Developments in wearable inertial sensor technology are now
142 facilitating performance evaluation on the field rather than in the laboratory [40]. Nevertheless, when investigating
143 dynamic movements (e.g. jumping), the validity of lower extremity joint kinematics in the frontal and transverse
144 planes is currently only deemed ‘fair-to-good’ (i.e. on a scale of ‘poor; ‘fair-to-good’; ‘excellent’) and thus
145 warrants further developments [41].

146 Efforts to improve the athlete-environment relationship will likely increase complexity of the dataset due to an
147 increase in the number of uncontrolled variables. Researchers are therefore challenged with finding the balance
148 between the preservation of the athlete-environment coupling and the interpretation of the dataset. For instance,
149 navigating around training dummies introduces more coordinative complexity when compared to preplanned
150 sidestep cutting. Likewise, replacing training dummies with real opponents adds additional coordinative

151 complexity, as well as variables related to affordance perception [16]. We advise to take small steps on this
152 spectrum of athlete-environment preservation, so that it aids the interpretation of the increasingly complex datasets.

153 **3.2 Including behaviour and the playing situation in the injury causation model**

154 It has long been popular to study ACL injury risk using a biomechanical approach [42, 43]. A goal of this approach
155 is to identify modifiable risk factors that can provide information for prevention strategies [5]. The focus typically
156 lies on describing biomechanical characteristics at a specific foot contact during a change-of-direction or landing
157 from a jumping movement [44, 45]. The movement tasks that are investigated are designed to mimic the
158 movements during which ACL injuries occur. This approach is appropriate for research regarding the internal and
159 external joint loads of such movement tasks, and it may serve as a ‘stepping stone’ to facilitate the interpretation
160 of more complex models. However, this approach is incomplete for a comprehensive understanding of actual
161 injury mechanisms[46].

162 ACL injury risk research demands an approach that is based on a more comprehensive injury causation model. In
163 2005, Bahr and Krosshaug [47] proposed a conceptual model describing the factors that contribute to the inciting
164 event of an injury. According to this model, the description of an inciting event should not only include information
165 about the biomechanical characteristics, but also about the playing situation and the behaviour of the athlete and
166 other players. Descriptive video analyses have shown that athlete behaviour and playing situations are highly sport-
167 specific [48, 49]. This highlights the importance of athlete behaviour and playing situations in the inciting event
168 of injury and thus supports the inclusion of these factors in the injury causation model that researchers adopt.

169 To determine the effects of player behaviour and playing situations on injury risk, we suggest designing
170 experiments that preserve the athlete-environment relationship while considering factors such as perceptual skills
171 and decision making of the athletes (e.g [50]) For instance, by studying the visual exploratory behaviour of athletes,
172 it might be possible to link visual exploratory behaviour prior to an action with the biomechanical characteristics
173 during the action [51]. Taken together, adopting this comprehensive injury causation model likely expands our
174 understanding of injury risk and thus may inform new prevention strategies.

175 **3.3 Comprehensive movement analysis requires non-reductionist methods**

176 A movement pattern is a series of movements over time. The reduction of this time series during analysis needs to
177 retain the information of interest regarding the research questions. In injury risk studies, researchers typically

178 analyse the kinematics of movements using linear descriptives such as means, ranges and standard deviations. The
179 results are often joint-specific snapshots of the mechanical properties during short time windows, e.g. peak knee
180 valgus moment during weight acceptance [11]. Researchers then compare the kinematics or kinetics to examine
181 differences between groups, interventions, conditions, or exercises. In this section, we will describe how this
182 ‘reductionist analysis’ often reduces the data to such an extent that it discards important information regarding
183 injury risk. We then discuss how the use of linear descriptives overlooks relevant information and propose a few
184 non-reductionist (i.e. more holistic) methods that provide profound information that helps our understanding of
185 injury risk mechanisms.

186 The reduction of a series of movements to a short time window neglects information regarding preceding
187 movement behaviour. By doing so, information regarding movement strategies that constitute safe biomechanical
188 characteristics is neglected. Alternatively, safe biomechanics may have involved unsafe preceding movement
189 behaviour. For example, the penultimate step of a change-of-direction has shown to provide important information
190 for the description of the movement behaviour prior to an injury [52]. Including the previous steps into the window
191 of analysis provides information regarding movement strategies that facilitate the biomechanics at final contact.
192 By expanding the measurement window, the information that constitutes the variable of interest is retained. This
193 allows for the extraction of information regarding safe movement strategies which is essential for informing
194 prevention programmes. An example of a linear analysis method that is appropriate for analysing time series is
195 statistical parametric mapping (SPM) [53].

196 Experimental studies usually collect their data through multiple trials of a movement task. As movement patterns
197 differ between trials [54], within-person movement variability is ever present in the data. The kinematic study of
198 movements therefore inevitably involves movement variability. Traditionally, variability is considered noise and
199 quantified as the deviation from the mean [54]. There are a few important limitations in the analysis of movement
200 variability using linear descriptives. First, the use of linear descriptives assumes that lower variability equals a
201 more stable system with less noise. However, there are examples where movements with high variability are more
202 deterministic (i.e. predictable variability), which shows greater stability in a movement [54, 55]. Variability
203 therefore requires a measure other than the standard deviation to describe the stability of movement patterns.
204 Second, linear descriptives reduce a time series to a single description, discarding any information regarding the
205 temporal structure of variability [54]. Third, the comparison of effects between groups can be inaccurate, as within-
206 person variability may be higher than between-group variability [56, 57]. Fourth, when assessing the effect of a

207 constraint on a movement task, the effect can differ between individuals, which violates the assumption of
208 homogeneity of linear testing models [57].

209 Human movement is inherently variable and this plays a vital role in the adaptability and coordination of the
210 movement system [58]. There are a few analysis methods that provide profound information that linear analysis
211 methods do not provide. First, the uncontrolled manifold (UCM) hypothesis relates variability towards a
212 performance variable that the movement system aims to control [59]; variability is divided into variability that
213 affects the performance variable and variability that does not. This way, UCM-based analysis does not solely
214 quantify variability, but offers the possibility to relate it to a performance measure of movement [59]. Second, the
215 Lyapunov exponent gives a description of the stability of the system in repeating movements, offering the
216 possibility to measure stability in a variable movement pattern [54]. For example, a decrease in functional
217 responsiveness (i.e. the response to a perturbation) has been shown in the ACL-deficient knee of athletes using
218 Lyapunov exponents [60]. Third, entropy analysis methods such as the approximate [61], multiscale [62], or
219 sample entropy [63], allow for the description of the rigidity of the system [54, 64]. By comparing the rigidity
220 of a system between conditions, the effect of the condition can be described while within-movement variability is
221 not neglected. For example, increased variability has been revealed in the acceleration of rugby players in a ball
222 situation compared to a no-ball situation [62].

223 The use of non-reductionist analysis methods such as the UCM, Lyapunov exponent, and entropy analysis provides
224 profound information regarding the coordination of the motor system and its response dynamics that linear
225 measures do not provide. For example, approximate entropy analysis found significant differences in postural
226 control between previously concussed participants and healthy controls, while the initial analysis using linear
227 statistics deemed participants to be recovered of their concussion [61]. However, despite their value, there are
228 limitations to the use of these methods. For instance, the sample entropy analysis of biomechanics in cyclical
229 movements is sensitive to changes in the trajectory of the movement [63]. Likewise, the calculation of the
230 Lyapunov exponent requires repeated movements within a trial. To add, most non-reductionist methods require a
231 larger sample size to correctly analyse variability (e.g. [65, 66]). Nevertheless, expanding the toolkit used in injury
232 risk research with non-reductionist methods in appropriate situations will allow researchers to extract information
233 which linear measures otherwise neglect. As a result, it will improve the understanding of the relationship between
234 the coordination of the motor system, the role of movement variability, constraints and injury risk.

235 **4 A study design that adheres to these three principles**

236 To exemplify the use of these principles, let us imagine a study that aims to examine the effect of fatigue on the
237 kinematics of sidestep cutting in a ball vs. no ball condition, aimed towards football research. The *athlete-*
238 *environment coupling* would be preserved by capturing kinematic data on the football pitch using inertial sensors.
239 Participants would perform sidestep cuts around training-dummies, allowing for the movement to self-organise
240 closer to how it would in real matches. The real-world constraints would be mimicked by inducing sport specific
241 fatigue through a football match simulation [67]. The study would *include behaviour and the playing situation to*
242 *the injury causation model* by investigating a potential confounding or mediating effect of visual exploratory
243 behaviour by testing conditions with and without ball possession. Furthermore, the study would comply with the
244 principle of *non-reductionist analysis* by complementing linear descriptives with an UCM analysis. Using the
245 UCM analysis, changes in the variability of joint-angles can be related to a control strategy such as the stability of
246 the centre of mass of the athlete [68]. This analysis may identify mechanisms between fatigue and unstable
247 movements. Such mechanisms may lead to the identification of novel risk factors, which can then be used to
248 identify players that are at increased risk of fatigue-induced injury. The results of the study would be discussed in
249 the context of the experiment and related to the context of the performance environment [14]. As changes in
250 behaviour are non-linearly related to movements (see section 2), an explicit description of the context of the
251 experiment would be required, allowing for a better comparison of effects between studies and providing
252 suggestions for future research.

253 **5 Conclusion**

254 This paper presents an ecological dynamics approach to injury risk research through three principles. It is important
255 to realise that the implementation of only one of these three principles will not yield the desired effect. For example,
256 maintaining the athlete-environment coupling whilst using only linear measures will still neglect relevant
257 information. Using non-reductionist (i.e. more holistic) methods in a non-representative lab setting does not
258 provide profound information regarding the performance context, limiting the generalisability of the results.
259 Similarly, limiting the research scope with a strictly biomechanical approach to injury causation prevents the
260 possibility to span results across relevant fields. Thus, the implementation of this ecological dynamics approach
261 warrants a simultaneous consideration of all three principles.

262 Undoubtedly, conducting research according to these theoretical principles poses practical challenges that warrants
263 attention. Firstly, efforts to preserve the athlete-environment relationship may increase the complexity of datasets.
264 Researchers should therefore take small steps in preserving the athlete-environment relationship in order to aid the

265 interpretation of these increasingly complex datasets. Secondly, when including playing situations and behaviour
266 in the injury causation model, it may help to form multidisciplinary research groups (e.g. biomechanists, sport
267 psychologists, coaches/trainers) and learn from each other's perspectives. Thirdly, to correctly implement non-
268 reductionist analyses, researchers should adjust their study designs so that they meet the requirements of the
269 analysis methods (e.g. sufficient sample size, appropriate measurement window). By collaborating with
270 statisticians, mathematicians, or other experts, researchers can explore the wealth of available methods to find
271 appropriate analyses for their research questions. We believe that studies using this approach will be more
272 generalizable and less reductionist. This results in improved understanding about risk factors and injury
273 mechanisms, thereby contributing to the sequence of prevention.

274 **Declarations**

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276 **Conflict of interest** The authors declare no conflicts of interest for this paper.

277 **Author contributions** Bolt and Heuvelmans wrote the manuscript. Benjaminse, Gokeler, and Robinson provided
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