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The 'vicious circle' of sports injuries: an analysis of 165 athletics (track and field) athletes over a 39-week follow-up using Markov chains

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ABSTRACT

Objective To explore (1) the risk of injury according to the number of previous injuries, and (2) the risk of progression of the athletes' health status according to the impact on athletics participation (ie, no injury/healthy (H), injury with full athletics participation (IF), injury with partial athletics participation (IP) or injury with no athletics participation (IN)).

Methods We performed a secondary analysis of injury data weekly collected using an online self-reported questionnaire from 165 athletics (track-and-field) athletes during 39 weeks. Using Markov chains, we determined the probabilities of (1) sustaining an injury with participation restriction (ICPR=IP+IN) depending on the number of previous ICPR and (2) transitioning from any one injury state to any other (ie, H, IF, IP, IN). Comparisons were made by calculating the ratio and 95% CIs between two probabilities using a bias-corrected accelerated bootstrap method.

Results Compared with the risk of the first ICPR, the risk of a second, third and fourth ICPRs increased on average by 1.9 (1.33 to 2.73), 2.2 (1.43 to 3.56) and 2.42 (1.37 to 4.41) times, respectively. Compared with having no injury (H), experiencing an IF at a given week had a five times higher risk of transitioning to an IP or IN the following week.

Conclusions Subsequent injuries show a higher risk than the first injury. Worse health states at a given week had a higher risk of worsening the following week. Our results highlighted a 'vicious circle' of injuries in athletics.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Understanding the injury aetiology and risk factors is important in developing strategies to reduce injury risk in athletics (track and field).
⇒ Having had a previous injury was reported in several studies in athletics and other sports as a risk factor for injuries.
⇒ To improve injury risk reduction, there is an interest in better understanding the athletes' future health status according to their current health status and injury history.

WHAT THIS STUDY ADDS

⇒ The risk of sustaining an injury increased approximately twofold after the first injury.
⇒ The worse the impact of an injury in a given week, the higher the risk of the impact worsening the following week.
⇒ Compared to being injury-free, athletes who experience an injury which does not restrict participation were at higher risk of sustaining a participation-restricting injury the following week.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Injuries that do not affect participation should not be ignored but managed, as they carry a fivefold increased risk of leading to participation restriction in the following week compared to healthy status.
⇒ Given the reported increase in the athletes' risk of sustaining a new injury as soon as they recover from the previous one, it can be important for athletes and their entourage to keep considering every injury and manage it appropriately.
⇒ According to the concept of the 'vicious circle' of sports injuries, it seems fundamental to reinforce the effort to reduce the risk of the first episode of injury.

INTRODUCTION

As in other sports, participation in athletics (track and field) is associated with a risk of sustaining injuries.[1] In the quest to develop strategies to reduce injury risk, better understanding the injuries' aetiology and risk factors has been considered an important step.[2] Among the factors associated with athletics injuries,[1] having sustained a previous injury was reported in several studies in athletics[3–7] and other sports.[8 9] This was not confined to recurrent injuries of the same anatomical location but to subsequent injuries in different locations and tissues.[3–9] Possible explanations could be incomplete tissue healing after an injury, a detraining/deconditioning of the body tissues during recovery from injury, and/or interference of the injury with physical conditioning and technical preparation.[6 7 10 11]

To our knowledge, previous studies only analysed the association between the history of previous injuries (eg, during the previous season(s)) and the occurrence of a new injury during the study follow-up[3 7] without exploring if the athletes' injury risk changed within the follow-up as additional injuries accumulated. Given the aforementioned possible explanations of how injuries could increase the risk of future injuries and based on the recursive model of sports injuries suggesting that risk factors may dynamically change after an injury event,[12] we can hypothese that, as soon as an athlete sustains the first injury, there could be a higher risk of recurrent/subsequent injuries, and despite a complete return-to-sport, this risk may never regress to the same levels as before sustaining the first injury. This could also imply that the risk of a new injury may keep increasing as the number of previously sustained injuries increases. This situation could be described as a 'vicious circle' of injuries.[13]

A similar 'vicious' situation could be hypothesised regarding the progression of the severity and/or the consequences of injuries in athletics practice. Indeed, some injuries do not impact/change the athletics practice. Some lead to modified/reduced practice, and others lead to total cessation of practice.[1 14] Questionnaires have been developed to better capture these different injury states of participation restriction.[3 15 16] Based on the questionnaire of Edouard *et al*,[15] the athletes' injury health status could be either (1) no injury/healthy (H), (2) injury with full athletics participation (IF), (3) injury with reduced (partial) athletics participation (IP) or (4) injury with no athletics participation (IN). Despite routinely collecting such information, little is known about how the health status evolves. For example, Whalan *et al*[17] reported in semi-professional football players that non-time-loss injuries were associated with a three to six times higher risk of sustaining a new time-loss injury within the subsequent 7 days after recovering from the initial non-time-loss injury. However, whether the same non-time-loss injury was more likely to progress to a time-loss injury than being healthy was not explored. By extending the concept of the 'vicious circle' of injuries, we could hypothesise that the bigger the participation restriction caused by an injury at a given week, the higher the risk of progression to a more severe status of participation restriction the following week.

In this context, with the overall goal of improving injury risk reduction in athletics, there is an interest in better understanding the athletes' future health status according to their current health status and injury history. Therefore, we aimed to explore (1) the risk of injury according to the number of previous injuries and (2) the risk of progression of the athletes' health status according to its current impact on athletics participation (ie, H, IF, IP and IN).

METHODS

Study design and overall procedure

We conducted a secondary analysis of the weekly injury data collected using an online self-reported questionnaire in athletics (track and field) athletes during 39 weeks of the 2017–2018 athletics season in the randomised controlled trial 'PREVATHLE'.[15] The use of the data for the present study was reviewed and approved by the Saint-Etienne University Hospital Ethical Committee (Institutional Review Board: IORG0007394; IRBN IRBN292023/CHUSTE). All athletes were informed about the study aim and procedure, that their data is used for research, and their rights to refuse it. For the present secondary analysis, no signed informed consent was required by the Ethical Committees.

Patient and public involvement

There was no public or patient involvement.

Equity, diversity, and inclusion statement

All athletes licenced at the French Federation of Athletics (FFA) in a club of at least 15 athletes and aged between 15 and 40 years were eligible for this study without any restriction based on sex, race/ethnicity/culture, socioeconomic level or representation from marginalised groups. Apart from sex and age, no other sociodemographics were collected from the participants and considered in the analysis and interpretation of results.

The author team included one junior and one senior researcher from sports medicine, physical medicine and rehabilitation, as well as two European countries (France and Greece).

Population

In this analysis, we included data from athletes who agreed to participate, provided written informed consent and met the inclusion criteria of the PREVATHLE study at the start of the 2017–2018 athletics season[15]: licensed at the FFA in a club of at least 15 athletes, aged between 15 and 40 years, having internet access and no contraindications for competitive athletics activity attested by the licence at the FFA. We included only those participants who answered the baseline questionnaire and provided 100% of the weekly responses.

Injury definition and data collection

Injuries were self-reported, and thus, they represented physical complaints (named 'injury complaints') rather than medically diagnosed injuries.[6 10 15 18 19], An *injury* was defined as: 'a pain, physical complaint or musculoskeletal lesion sustained by an athlete during participation in athletics training or competition, regardless of whether it received medical attention or its consequences concerning impairments in connection with competition or training".[6 10 15 18 19]

Athletes were asked to report their status regarding any injury (1) during the previous season using an online Google Forms survey at the start of the season and (2) during the previous week using a secured website called

'Prevathle' (Windows Server 2013 R2 64 bits – SP2; IBM DOMINO 9.01 fix pack 8) weekly over the 39-week follow-up, by selecting one of the four following categories: (1) healthy (ie, no injury) (H), (2) injury with full athletics participation (IF), (3) injury with partial athletics participation (IP) and (4) injury with no athletics participation (ie, time-loss) (IN).[15] The last two categories (IP and IN) corresponded to injury complaints with participation restriction (ICPR).[15]

In addition, at the start of the 2017–2018 athletics season, we collected baseline information from each included athlete using the Google Forms survey: sex, age, height, body mass, athletics discipline, duration of usual weekly athletics training (in hours) and duration of usual weekly non-specific sports training (in hours).[15] During the 39-week study follow-up, we prospectively collected the following information using a weekly self-reported online questionnaire on the secured website called 'Prevathle': athletics exposure (training and competition, hours and intensity), sport outside of athletics exposure (training and competition, hours and intensity), and any illnesses.[15]

Data processing: Markov chains development

A Markov chain (a.k.a. Markov model) describes how a variable of a finite set of values (a.k.a. states) is transitioning from one state to another over a period, which is divided into units of time so that one unit corresponds to one state transition.[20,21] It comprises a set of states and the corresponding transitions from any state to any other (including itself).[20] Each transition is associated with a probability reflecting the likelihood of transitioning from the starting state to the ending state.[20] Thus, the probability of transitioning from a healthy state to an injured state can reflect the risk of injury in sports injury. Similarly, the probability of transitioning from an injury state to the same injury state (ie, the probability of remaining in the same state of participation restriction) can reflect the expected duration of that state before transitioning to a different state. Markov chains have already been applied to model the risk of medical conditions such as diabetes mellitus[22] and migraine attacks.[23]

For the present analysis, we developed one Markov chain from the observed data of our population for each of the two study objectives. We considered each athlete's week-by-week responses to injury status over the 39-week follow-up, and we used Markov chains to analyse the probability of transitioning from one state of injury to another from 1 week to the next.

For the first study objective, we merged the four injury complaint categories into 2: *No-ICPR* (*H* and *IF*) and *ICPR* (*IP* and *IN*). Then, we tagged each state with an index number corresponding to how many ICPRs the athlete has sustained so far (eg, *No-ICPR-0*, *ICPR-1*, *No-ICPR-1*). This way, a healthy state (*No-ICPR-n*) could only transition the following week to either itself (*No-ICPR-n*) or the next injury state (*ICPR-(n+1)*). Similarly, an injury state (*ICPR-n*) could only transition the following week to either itself (*ICPR-n*) or the next healthy state (*No-ICPR-n*) (figure 1A). Thus, the total number of transitions would depend on the maximum number of ICPRs sustained by the athletes.

For the second objective, we considered the four states (H, IF, IP, IN) separately without accounting for the number of ICPRs sustained. There was, thus, a total of 16 transitions (figure 1B).

To construct the Markov chain of each objective, we used each athlete's week-by-week injury status encoded either in two states (objective 1) or four states (objective 2) (figure 2A). We defined the transitions from any one state to any other (figure 2B), and we counted the number of transitions from any one state to any other (figure 2C). If some transitions were never observed for one athlete, their count was 0. Then, we added the counts of each transition observed by all athletes (figure 2D). Finally, for each transition, we divided its count by the sum of those transitions that had the same starting state with that transition (figure 2E). This was equivalent to the probability of that transition. This process would produce a transition matrix with values corresponding to the transition probabilities from one state to another (figure 2E), which could be graphically represented with nodes as states and arrows as transitions (figure 2F).

Markov chains are based on the Markov principle, which states that the next state depends only on the current state.[24] In the context of sports injury, it is expected that the future state of injury can be influenced not only by the current state but also by the previous state. So, it could be argued that higher-order Markov chains (ie, second or third-order Markov chains, where the two or three last states are considered to determine the future state, respectively[24]) could better model the injury status over a period of time. However, our aim was not to develop accurate forecasting models but to describe injury risk from observed data, highlighting the importance of low model complexity. Thus, we compared the first-order with the second-order model using the Bayesian information criterion, which showed that the first-order model had the best combination of good data-fitting and low complexity for the second study objective online supplemental material A. Regarding the first objective, the model had already incorporated some time dependence by the sequential indexing of ICPRs.

Statistical analysis

We performed a descriptive analysis of the included population using frequency and percentages for categorical variables and medians and IQRs for continuous variables of non-normal distribution. Results of the transition probabilities and their ratios were presented with 95% CIs and at three decimal places. To calculate the 95% CIs of the observed transition probabilities, we performed a bias-corrected accelerated bootstrapping technique of 1000 samples by resampling from the original population of athletes.[25] According to this, we repeated the same process of Markov chain development

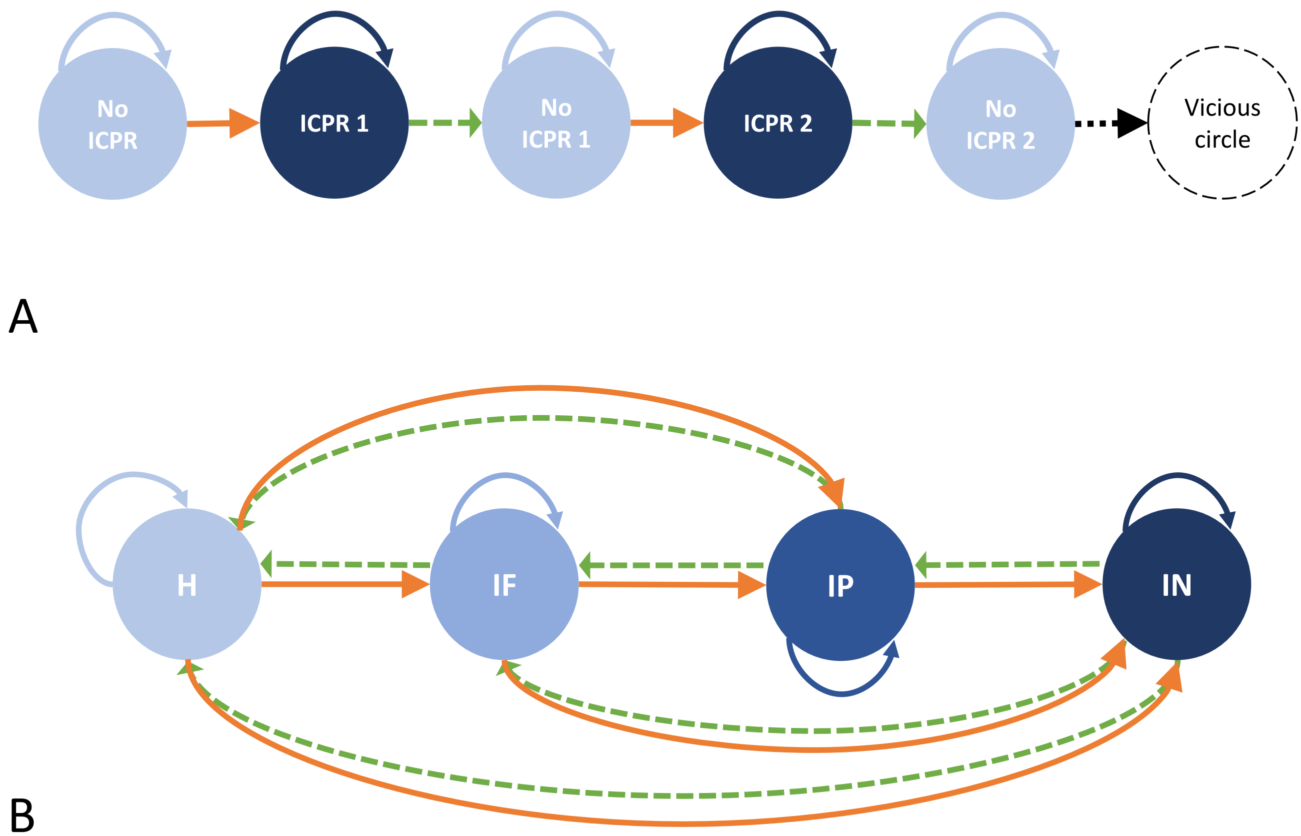

Figure 1 Illustration of the Markov chains developed to explore the risk of injuries according to (1) the number of previous injuries (A), and (2) the athletes' health status (ie, no injury (H), injury with full athletics participation (IF), injury with partial athletics participation (IP), injury with no athletics participation (IN)) (B). For the study objective 1 (A), the transitions from no injuries with participation restriction (No ICPR) state to injuries with participation restriction (ICPR) state (orange arrows) reflect an injury risk, the transitions from No ICPR state to the same No ICPR state (light blue arrows) reflect the availability to athletics practice without ICPR, and the transitions from ICPR state to the same ICPR state (dark blue arrows) reflect the probability to remain in that injury state, and the transitions from ICPR state to no ICPR state reflect the healing process (dotted green arrows). This forms an open-chain Markov process modelling the 'vicious circle' of injuries. For study objective 2 (B), the transitions from a less participation-restrictive state to a more participation-restrictive state (orange arrows) reflect an injury risk. The transitions from an injury state to the same state (blue arrows) reflect the maintenance of the injury consequence on the athletics practice (ie, maintenance of participation restriction), and the transitions from a more participation-restrictive state to a less participation-restrictive state reflect a decrease in the injury consequence on athletics practice (dotted green arrows). This forms a closed-chain Markov process modelling the weekly transition between the four injury states.

with each sample of athletes' data. In the end, we had a 1000-sample distribution of each transition probability of the original chain. This distribution and the probability from the original population were used to derive the 95% CI of each transition probability. Since the distributions of transition probabilities were constrained between 0 and 1, skewness around the original values was expected. To account for this, the bias-corrected accelerated technique was selected instead of the percentile bootstrap technique.[25]

Since the outcomes of this study were the transition probabilities and the whole population data was used to derive one measurement of the transition probabilities, we could not compare them using hypothesis testing. Instead, to compare two transition probabilities, we calculated their ratio. These ratios' 95% CIs were derived by computing the ratios in each of the 1000 transition matrices derived from the bootstrapping technique described above. Two probabilities were considered significantly different if their ratio's 95% CI was entirely above or entirely below 1. To our knowledge, there is no standard method to calculate a Markov chain analysis sample size, so we only conducted an a posteriori power analysis.

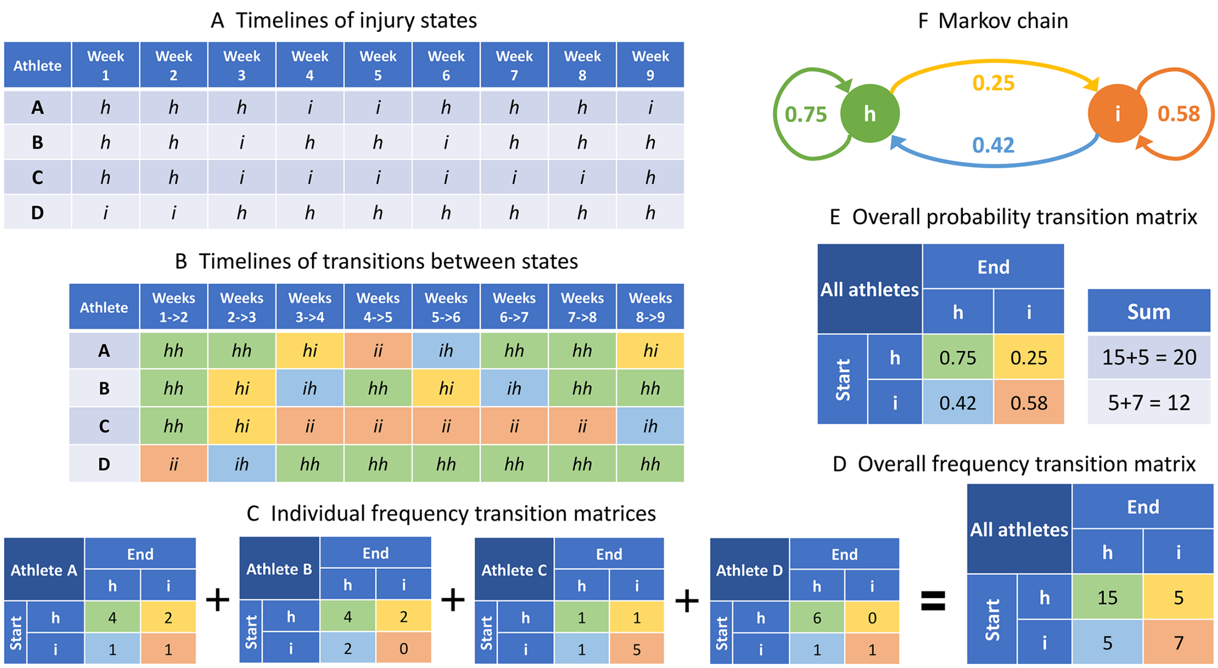

Figure 2 Step-by-step example of creating a two-state Markov chain model using fictitious weekly injury data from a group of athletes. (A) The athletes' raw data of timelines shows the injury status (healthy 'h' or injured 'i'). (B) Transform of the timelines to transitions between injury states (eg, from healthy to injured: h→ i = 'hi') of consecutive time points. (C) Each timeline of transitions is summarised in a transition matrix showing how many times each transition was observed (frequency). (D) The individual transition matrices are summed (cell-by-cell), creating the overall transition matrix of frequencies. (E) By dividing each cell of the frequency matrix with the sum of observations in each row (ie, how many transitions shared the same starting state), the probability matrix is created, showing the probability of transitioning to an ending state given a starting state. (F) The Markov chain can be visualised by plotting the states as nodes in a graph, interconnected by arrows indicating the probability of transitioning from the start of the arrow to the end.

Data processing and statistical analysis were conducted in Python (https://www.python.org/). The code used for the development of Markov chains and the bootstrapping technique can be accessed here:

https://github.com/spyrosiatrop/Vicious_circle_of_injuries_Markov_chain_analysis.

RESULTS

Population

From the 840 included athletes in the 'PREVATHLE' study, 165 satisfied all inclusion criteria of this study. Their baseline characteristics are summarised in online supplemental material. From them, 57 (34.5%) athletes reported no ICPR, 43 (26.1%) athletes reported only one ICPR, while the remaining 65 (39.4%) athletes sustained at least two ICPR, for a total of 242 ICPR from 108 athletes over the follow-up (online supplemental material C).

Objective 1: transitioning to injury depending on the number of previous injuries

The risk of ICPR increased significantly from the first ($P_{risk,ICPR1}$=0.027 (0.021 to 0.033)) to the second ($P_{risk,ICPR2}$=0.051 (0.038 to 0.067)) ICPR occurrences by ~90% ($ratio_{2/1}$=1.897 (1.331 to 2.724)) (tables 1 and 2, and figure 3). The risk of the third ICPR ($P_{risk,ICPR3}$=0.059 (0.04 to 0.086)) was ~16% higher than the second, and the risk of the fourth ICPR ($P_{risk,ICPR4}$=0.065 (0.039 to 0.111)) was ~10% higher than the third ICPR, although these descriptive findings were not statistically significant ($ratio_{3/2}$=1.161 (0.748 to 1.919); $ratio_{4/3}$=1.099 (0.596 to 2.262)). Nonetheless, compared with the risk of the first ICPR, the third and fourth ICPR were significantly higher by more than twofold (tables 1 and 2, and figure 3). The a posteriori power analysis indicated a power of ≥80% for the significant and ≤4% for the non-significant findings (online supplemental material D).

The probability of remaining on injury did not change significantly between the first ($P_{remain,ICPR1}$=0.648 (0.547 to 0.738)), second ($P_{remain,ICPR2}$=0.592 (0.474 to 0.681)), third ($P_{remain,ICPR3}$=0.625 (0.392 to 0.771)) and fourth ICPR ($P_{remain,ICPR4}$=0.667 (0.478 to 0.800)) (tables 1 and 2, and figure 3).

Objective 2: transitioning between injury states

Compared with having no injury (H), experiencing an IF at a given week had a significantly higher risk of transitioning to an IP ($P_{IF\text{->}IP}$=0.123 (0.089 to 0.166); $P_{H\text{->}IP}$=0.022 (0.017 to 0.027); ratio=5.657 (3.916 to 8.125)) or an IN ($P_{IF\text{->}IN}$=0.043 (0.024 to 0.066); $P_{H\text{->}IN}$=0.008 (0.006 to 0.011); ratio=5.203 (2.804 to 8.972)) the following week (tables 3 and 4, and figure 4). Similarly, experiencing an IP at a given week had a significantly higher risk of transitioning to an

Table 1 Transition probabilities between healthy (no-ICPR) and injury (ICPR) states are based on the number (n) of sustained injuries with participation restriction (ICPR) (mean (95% CI)). The transition probabilities to remain in the same injury state (from ICPR-n to ICPR-n) are presented in the first column. The transition probabilities from a healthy state (no-ICPR-n) to the next injury state (ICPR-(n+1)) are equivalent to the risk of each injury (last column). By comparing the values of each column, we can see how the transition probability from one state to another is influenced by the number of ICPR sustained by the athletes. The table can be linked to figure 3 through the coloured arrows of each column

Transition from:	ICPR-n		No-ICPR-n	
Arrow (figure 3):	→	→	→	→
Transition to:	**ICPR-n**	**No-ICPR-n**	**No-ICPR-n**	**ICPR-(n+1)**
n=0	–	–	0.973 (0.967 to 0.979)	0.027 (0.021 to 0.033)
n=1	0.648 (0.547 to 0.738)	0.352 (0.262 to 0.453)	0.949 (0.934 to 0.962)	0.051 (0.038 to 0.067)
n=2	0.592 (0.474 to 0.681)	0.408 (0.319 to 0.522)	0.941 (0.914 to 0.961)	0.059 (0.040 to 0.086)
n=3	0.625 (0.392 to 0.771)	0.375 (0.229 to 0.606)	0.935 (0.889 to 0.961)	0.065 (0.039 to 0.111)
n=4	0.667 (0.478 to 0.800)	0.333 (0.192 to 0.514)	0.940 (0.866 to 0.974)	–

IN the following week ($P_{IP\text{->}IN}$=0.102 (0.076 to 0.134)) compared with experiencing an IF ($P_{IF\text{->}IN}$=0.043 (0.024 to 0.066); ratio=2.401 (1.455 to 4.623)) (tables 3 and 4, and figure 4). The a posteriori power analysis estimated that power was larger than 90% for these findings (online supplemental material D). The probability of remaining in the same state of participation restriction of an IN ($P_{remain,IN}$=0.568 (0.458 to 0.658)) was significantly higher than that of an IF ($P_{remain,IF}$=0.396 (0.292 to 0.516); $R_{IN/IF}$=1.434 (1.026 to 2.015)) or an IP ($P_{remain,IP}$=0.430 (0.346 to 0.518); $R_{IN/IP}$=1.324 (1.092 to 1.674)) (figure 4, tables 3 and 4).

DISCUSSION

The main findings of the present study were that (1) compared with the risk of the first ICPR, the risk of a second, third and fourth ICPR increased on average by 1.9, 2.2 and 2.4 times, respectively, and (2) the worse the impact of an injury at a given week, the higher the risk of the impact to get worse the following week.

The macroscopic 'vicious circle' of injuries: a domino effect

Our results reported that, compared with the first injury, the risk of the second injury increased by 90% (33% to 172%), the risk of the third injury by 120%

Table 2 Ratios between two transition probabilities with a 95% CI from the Markov chain modelling the risk of injuries with participation restriction (ICPR) and the probability of remaining in the same injury state according to the number of previous ICPRs sustained. The coloured arrows indicate which transitions are being compared according to figure 3

Numerator transition	Denominator transition	Ratio of transition probabilities
		Risk ratio (mean (95% CI))
No-ICPR-1 → ICPR-2	No-ICPR-0 → ICPR-1	1.897 (1.331 to 2.724)*
No-ICPR-2 → ICPR-3	No-ICPR-0 → ICPR-1	2.203 (1.433 to 3.553)*
No-ICPR-3 → ICPR-4	No-ICPR-0 → ICPR-1	2.42 (1.377 to 4.408)*
No-ICPR-2 → ICPR-3	No-ICPR-1 → ICPR-2	1.161 (0.748 to 1.919)
No-ICPR-3 → ICPR-4	No-ICPR-2 → ICPR-3	1.099 (0.596 to 2.262)
		Remain-in-state ratio (mean (95% CI))
ICPR-2 → ICPR-2	ICPR-1 → ICPR-1	0.915 (0.696 to 1.159)
ICPR-3 → ICPR-3	ICPR-2 → ICPR-2	1.055 (0.680 to 1.416)
ICPR-4 → ICPR-4	ICPR-3 → ICPR-3	1.067 (0.703 to 1.905)

*Ratios were considered statistically significant if the CI was above or below 1.

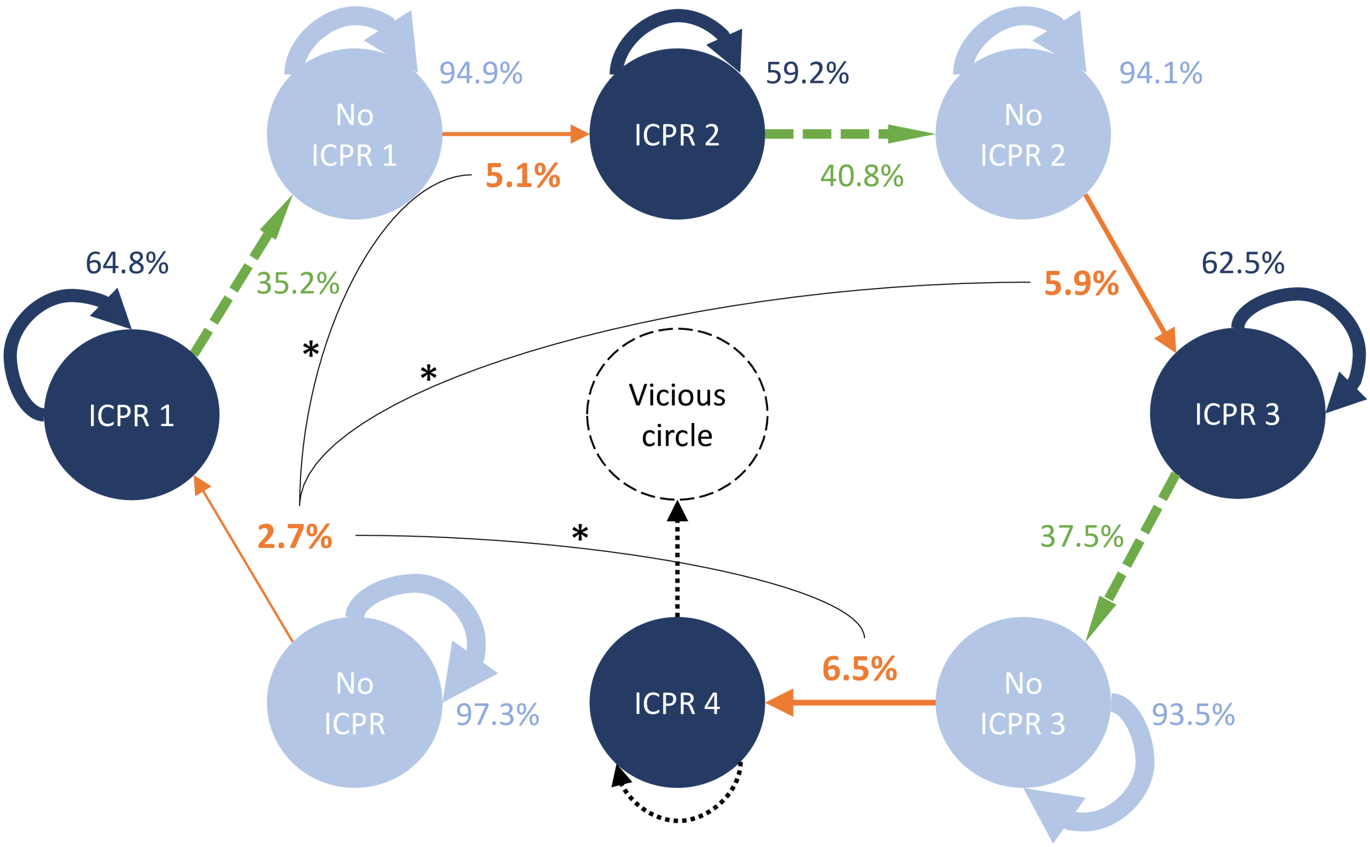

Figure 3 The open-chain Markov process modelling the 'vicious circle' of injuries. The transitions from no injuries with participation restriction (No ICPR) state to injuries with participation restriction (ICPR) state (orange arrows) reflect an injury risk. The transitions from the No ICPR state to the same No ICPR state (light blue arrows) reflect the availability of athletics practice without ICPR. The transitions from the ICPR state to the same ICPR state (dark blue arrows) reflect the probability of remaining in that injury state. The transitions from ICPR to no ICPR state reflect the healing process (dashed green arrows). *Statistically significant comparison (ie, the 95% CI of the ratio is entirely above or below 1).

(43% to 255%) and the risk of the fourth injury by 142% (38% to 341%), indicating that the injury risk never regressed to the same levels as before sustaining the first injury. Descriptively, we even observed additive risk increments of 16% (−25% to 92%) and 10% (−40% to 126%) after the second and third ICPR, respectively, although these were not statistically significant and should be considered with caution. Nonetheless, the clinical significance of these findings warrants more studies with larger datasets and sufficient power to better estimate the additional risk after each sequential injury. Collectively, these findings represent one argument in favour of our hypothesis of a 'vicious circle' of injuries. Specifically, in the context of our study and its time frame, as soon as the athletes had a first episode of injury, their susceptibility (ie, risk) to sustain a new injury was no longer the same as before sustaining the injury. It was, however, impossible to determine if the risk could return to the baseline level and, if so, when.[26]

Table 3 Transition matrix with the probabilities of transitioning from any given starting state to any ending state (mean (95% CI)). Colours indicate the arrow colours of the respective transition in figure 4

		Ending injury state			
		H	IF	IP	IN
Starting injury state	H	0.940(0.930 to 0.949)	0.030(0.024 to 0.037)	0.022(0.017 to 0.027)	0.008(0.006 to 0.011)
	IF	0.439(0.331 to 0.539)	0.396(0.292 to 0.516)	0.123(0.089 to 0.166)	0.043(0.024 to 0.066)
	IP	0.320(0.255 to 0.392)	0.148(0.110 to 0.195)	0.430(0.346 to 0.518)	0.102(0.076 to 0.134)
	IN	0.170(0.121 to 0.236)	0.035(0.011 to 0.069)	0.227(0.158 to 0.300)	0.568(0.458 to 0.658)

H, healthy (ie, no injury); IF, injury with full athletics participation; IN, injury with no athletics participation (ie, time-loss); IP, injury with partial athletics participation.

Table 4 The ratio (numerator/denominator) comparisons of the risk transition probabilities (upper part of the table) and the probabilities of remaining in the same injury state (lower part of the table). The probabilities of transitioning from a worse to a better state were not compared (green colour in table 3). A ratio has been estimated by dividing a transition probability (column headings) by another transition probability (row headings). The ratios mentioned in the main text are in bold

		Transition probability (numerator)				
		H → IP	H → IN	IF → IP	IF → IN	IP → IN
Transition probability (denominator)	H → IF	0.717* (0.543 to 0.947)	0.270* (0.182 to 0.378)	4.056* (2.723 to 5.832)	1.407 (0.773 to 2.337)	3.379* (2.385 to 4.707)
	H → IP	–	0.377* (0.254 to 0.539)	**5.657* (3.916 to 8.125)**	1.963* (1.053 to 3.303)	4.712* (3.337 to 6.795)
	H → IN		–	14.997* (9.687 to 23.073)	**5.203* (2.804 to 8.972)**	12.493* (8.281 to 19.659)
	IF → IP			–	0.347* (0.205 to 0.563)	0.833 (0.549 to 1.279)
	IF → IN				–	**2.401* (1.455 to 4.623)**
	Transition probability (numerator)					
		IP → IP	IN → IN			
	IF → IF	1.085 (0.789 to 1.529)	1.434* (1.026 to 2.015)			
	IP → IP	–	1.321* (1.092 to 1.674)			

*Ratios were considered statistically significant if the CI was above or below 1.
H, healthy (ie, no injury); IF, injury with full athletics participation; IN, injury with no athletics participation (ie, time-loss); IP, injury with partial athletics participation.

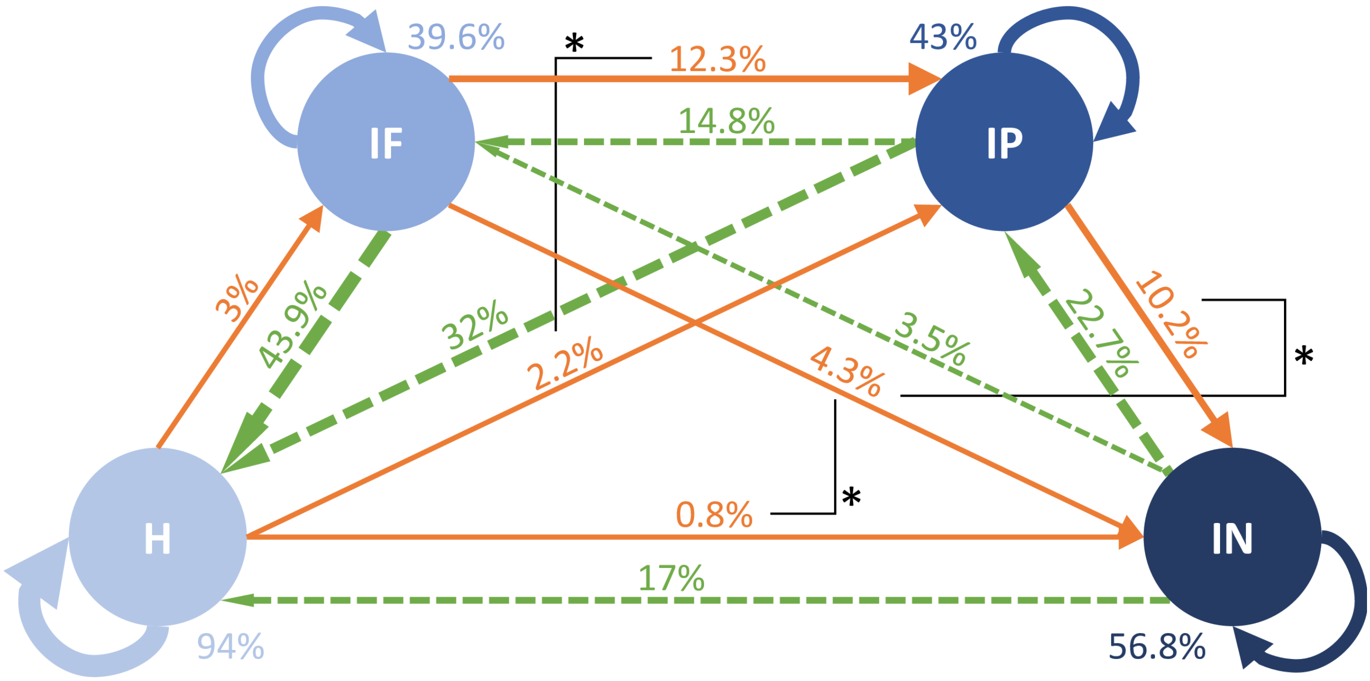

Figure 4 The closed-chain Markov process modelling the weekly transition between the four injury states with the transition probabilities. The transitions from a less participation-restricting state to a more participation-restricting state (orange arrows) reflect an injury risk. The transitions from an injury state to the same state (blue arrows) reflect the maintenance of the injury consequence on the athletics practice (ie, maintenance of participation restriction), and the transitions from a more participation restriction state to a less participation restriction state reflect a decrease in the injury consequence on athletics practice (dotted green arrows). The thickness of the arrows is proportional to the corresponding probability. The ratios comparing transition probabilities correspond to table 4. *Statistically significant comparison (ie, the 95% CI of the ratio is entirely above or below 1). H, healthy; IF, injury with full participation; IN, injury with no participation; IP, injury with partial participation.

Further research is needed to support the proposed mechanisms of this increase, including weakness of the injured tissue, detraining/deconditioning, and interference with training.[6 7 10 11]

The microscopic ‘vicious circle’ of injuries: a snowball effect

Our results also showed that the following week’s health status (ie, participation restriction) of athletes would depend on their previous week’s health status. Indeed, the worse the impact of the injury health status on athletics practice at a given week, the higher the risk for that impact to worsen the following week. For example, compared with being healthy, the experience of an injury without participation restriction (ie, non-time-loss injury) at a given week was five times more likely to progress to participation restriction the following week. This finding expands on the results of Whalan *et al*,[17] where footballers had a three to six times higher risk of sustaining a new time-loss injury within the subsequent week after recovering from a non-time-loss injury. Potential hypotheses explaining this finding pathophysiologically could include maladaptations in the biological, biomechanical, functional and/or psychological level, which then reduce the capacity of the tissue/body to tolerate previously manageable constraints, thus increasing the risk of worsening the injury. The first event can be seen as an alert or warning signal, indicating a weakness and/or poor condition that may worsen if not properly managed. Although the precise mechanism behind these risk differences requires further investigation, this finding matches our described concept of the ‘vicious circle’ of injuries: the more impactful the injury, the higher the risk of it worsening.

Methodological considerations

Given a lack of gold standard analyses to describe the time-dependent relationship of previous injuries to subsequent injury risk, Markov chain analyses offer a promising alternative to traditional statistical methods.

However, we have to acknowledge some limitations. Data were self-reported by the athletes without any medical diagnosis. How athletes determine the status of their injuries could be linked to their behaviour regarding injury management and participation restriction. Information on injuries was asked weekly, and in such a time frame, the injury status can vary over the 7 days. However, similar limitations exist in every self-reported weekly data collection approach.[16] Besides, in recreational and individual sports like athletics, a diagnosis-based injury data collection method could be prone to under-reporting injuries, especially minor injuries, since athletes may not ask for medical consultation for each physical complaint. Replicating such analyses with samples of medically diagnosed injuries could further validate the 'vicious circle' concept.

Additionally, the small sample size may have led to wide CIs of comparisons, especially those of less frequently observed events. For example, only 17 athletes sustained a third ICPR, of which only 12 sustained a fourth one (online supplemental material C). This limitation did not affect comparisons of more frequently observed events (eg, comparison between second and first ICPR), allowing us to support the concept of the 'vicious circle' of injuries. Future studies of larger sample sizes can explore a more accurate quantification of this concept. Similarly, we only performed an a posteriori power analysis, which had limitations[27] given the lack of a standard way to calculate sample size a priori for Markov chain analyses. Such post-hoc power analyses cannot be interpreted similarly to a priori ones, and they are less meaningful, especially for non-significant findings.[27] Thus, the very low 'observed' power of non-significant findings could imply that more data is required to estimate the compared quantities better (supplementary material D).

Moreover, the duration of the study was only over a season, which does not allow us to see the problem of injuries over the athletes' careers. Also, the included population of French athletics (track and field) athletes is not representative of other sports populations, so similar analyses in other sports and/or contexts are needed to assess the generalisation of these findings. Nonetheless, given that having sustained a previous injury was reported as a risk factor for new injury in several studies in athletics[3–7] and other sports,[8 9] we can hypothesise that the results could be similar in other sports and/or contexts. In the analysis, we included athletes who performed an injury prevention programme, although only six athletes did it as recommended, so the potential influence was considered very small.[15] Lastly, our study could not explore the mechanisms behind the reported results.

Practical implications

Given the reported change in athletes' injury risk as soon as there is an injury event, the results of our present study supported, with a data-driven approach, the previously introduced concept of the 'vicious circle' of injuries.[13] The clinical implications stemming from this can be that (1) we need to reinforce the efforts to avoid or delay the occurrence of the first injury, (2) we should not succumb to new injuries but persist in managing every single one as appropriately as possible and (3) we should not neglect symptoms that do not affect athletics participation but manage them as potentially participation-restricting injuries.

To achieve these goals, Edouard *et al*[13] have suggested that such injury risk reduction approaches should focus on youth athletes, targeting their most frequently reported injuries through a multifactorial approach. Evidence-based examples of effective injury risk reduction strategies can be found in athletics[28–30] and other sports,[31 32] but other methods should be evaluated.[1] One example is disseminating information about the relevance and implementation of injury risk reduction strategies among youth athletes by educating coaches, club leaders, parents and athletes.[28]

If a first injury occurs, our concept of the 'vicious circle' of injuries urges for appropriate management of every injury event, including, for instance, medical consultation for diagnosis followed by an optimal return-to-sport plan to reduce the sequelae and the number of recurrent and/or subsequent injuries. Indeed, for each injury episode, it is suggested that the best possible way to restore the injured tissue is to avoid its weakness while ensuring appropriate physical fitness of the entire body.[33]

Based on our finding that minor injuries can lead more frequently to time-loss injuries than sustaining a time-loss injury while being healthy the previous week, we propose that athletes and their entourage should not ignore injuries that do not restrict athletics participation but manage them appropriately to avoid their escalation. For instance, this can be achieved through medical consultation, physiotherapy assessment, load management and cessation of sport for some days.

From the perspective that the injury is inevitable and the athlete enters this 'vicious circle' of injuries, it can also be relevant to adopt a more 'virtuous' approach by trying to see the 'half-full glass' in a difficult period,[34] and by viewing an injury event as an opportunity to improve the injury prevention approaches.[35]

Future perspectives

Beyond the novel findings of this study, the proposed methodology of Markov chain modelling opens the door to a new way of perceiving and visualising injury risk through transition probabilities. Such analyses could be applied in different sports settings, using different injury definitions or specific types of injuries, providing a flexible and versatile tool to improve the comparability of findings from different study designs. Future studies could apply Markov models to intervention studies, for example, by comparing the transition probabilities reflecting injury risk between an intervention group and a control group, in studies aiming to identify injury risk factors, or in studies exploring the efficacy of rehabilitation and return-to-sport programmes.

A research implication of the present results is that collecting data on injury history may be more appropriate through a continuous variable (eg, how many injuries have been sustained) rather than a binary variable (eg, having sustained an injury or not).

CONCLUSIONS

This study used Markov chain analyses to support the hypothesis of a 'vicious circle' of injuries in athletics. The risk of subsequent injuries was approximately two times higher than the risk of sustaining the first injury. Also, the worse the impact of an injury in a given week, the higher the risk of the impact getting worse the following week. Based on these findings, we can suggest that (1) every injury should be taken into consideration and managed appropriately, (2) minor injuries should not be neglected since they could progress to injuries restricting participation and (3) efforts to reduce the risk of the first as well as subsequent injuries should continue.

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Patient consent for publication Consent obtained directly from patient(s).

Ethics approval In the present study, we used data from a randomised controlled trial that was approved by the Committee for the protection of persons (CPP Ouest II—Angers, number: 2017-A01980-53), and was registered in the ClinicalTrials.gov (ClinicalTrials.gov Identifier: NCT03307434). This present study and analysis were reviewed and approved by the Saint-Etienne University Hospital Ethical Committee (Institutional Review Board: IORG0007394; IRBN292023/CHUSTE).

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