THE DEVELOPMENT AND APPLICATION OF AN INJURY PREDICTION MODEL FOR NONCONTACT, SOFT-TISSUE INJURIES IN ELITE COLLISION SPORT ATHLETES

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ABSTRACT

Gabbett, TJ. The development and application of an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes. *J Strength Cond Res* 24(10): 2593–2603, 2010—Limited information exists on the training dose–response relationship in elite collision sport athletes. In addition, no study has developed an injury prediction model for collision sport athletes. The purpose of this study was to develop an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes. Ninety-one professional rugby league players participated in this 4-year prospective study. This study was conducted in 2 phases. Firstly, training load and injury data were prospectively recorded over 2 competitive seasons in elite collision sport athletes. Training load and injury data were modeled using a logistic regression model with a binomial distribution (injury vs. no injury) and logit link function. Secondly, training load and injury data were prospectively recorded over a further 2 competitive seasons in the same cohort of elite collision sport athletes. An injury prediction model based on planned and actual training loads was developed and implemented to determine if noncontact, soft-tissue injuries could be predicted and therefore prevented in elite collision sport athletes. Players were 50–80% likely to sustain a preseason injury within the training load range of 3,000–5,000 units. These training load 'thresholds' were considerably reduced (1,700–3,000 units) in the late-competition phase of the season. A total of 159 noncontact, soft-tissue injuries were sustained over the latter 2 seasons. The percentage of true positive predictions was 62.3% ($n = 121$), whereas the total number of false positive and false negative predictions was 20 and 18, respectively. Players that exceeded the training load threshold were 70 times more likely to test positive for noncontact, soft-tissue injury, whereas players that did not exceed the training load threshold were injured 1/10 as often. These findings provide information on the training dose–response relationship and a scientific method of monitoring and regulating training load in elite collision sport athletes.

KEY WORDS injury prevention, rugby league, training monitoring, training load, applied sport science

INTRODUCTION

The training–performance relationship is of particular importance to coaches to determine the optimum amount of training required to attain specific performance levels (2,5,11). Bannister et al. (4) proposed a statistical model to describe an athlete's response to a given training stimulus. According to this model, the performance of an athlete in response to training can be estimated from the difference between a negative function (fatigue) and a positive function (fitness). Studies have described the training–performance relationship as analogous with the dose–response relationship reported in pharmacological studies, with the primary goal of providing a training stimulus that maximizes performance potential and minimizes the negative consequences of training (i.e., injury, illness, fatigue, overtraining) (29).

Several studies have investigated the influence of training volume, intensity, and frequency on athletic performance, with performance generally improving with increases in training load (11,12,28,31,32,37,39). Studies of the training–performance relationship in individual sports (e.g., swimming and running) have found a positive relationship between both greater training volume and performance (12,39) and higher training intensity and performance (28,32,37). Foster et al. (11) studied 56 runners, cyclists, and speed skaters during 12 weeks of training and reported that a 10-fold increase in training load was associated with a ~10% improvement in performance. Moreover, Stewart and Hopkins (39) reported a significant relationship between greater training volume and performance ($r = 0.50–0.80$) and higher training intensity and performance ($r = 0.60–0.70$) in competitive swimmers. However, it has also been shown that negative adaptations to exercise training are dose related, with the

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highest incidence of illness and injury occurring when training loads are highest (10,17).

In contrast to individual sports, collision sports (e.g., ice hockey, rugby, and lacrosse) are characterized by large numbers of physical collisions and tackles, short repeated sprints, rapid acceleration, deceleration, and changes of direction, and an ability to produce high levels of muscular force extremely rapidly (19). As a result, collision sport athletes are required to have well-developed speed, strength, muscular power, agility, and maximal aerobic power ($\dot{V}O_2max$). Previous studies of collision sport athletes have reported a significant relationship ($r = 0.86$) between training loads and training-injury rates (17), suggesting that the harder these athletes train, the more injuries they will sustain. Furthermore, reductions in training loads have been shown to reduce training-injury rates and result in greater improvements in $\dot{V}O_2max$ (18). However, it has also been shown that collision sport athletes that perform <18 weeks of preseason training before sustaining an initial injury are at an increased risk of sustaining a subsequent injury, whereas players with a low off-season $\dot{V}O_2max$ are at an increased risk of sustaining a contact injury (20). Clearly, training for collision sports reflects a balance between the minimum training load required to elicit an improvement in fitness and the maximum training load tolerable before sustaining marked increases in injury rates.

The majority (~60%) of collision sport injuries have been shown to occur in physical collisions and tackles (14,15,23,24) and are therefore thought to be mostly unavoidable. However, a considerable proportion of injuries sustained by collision sport athletes are noncontact, soft-tissue issues that occur as a result of excessive training loads, inadequate recovery, and overtraining (15,17–19,21). These injuries, which are largely preventable, have the potential to impact team selections and as a result may influence team performance. Therefore, an obvious challenge for coaches is to identify the athletes that have received an adequate training stimulus to compete optimally and those that may be susceptible to overreaching or overtraining. However, no study has identified the optimum training load to minimize noncontact, soft-tissue injuries in collision sport athletes.

Although models of the training–performance relationship have been constructed for athletes from individual sports (2–4,10,11,30,31,39), studies of the training–performance relationship of collision sport athletes are limited (9,26) and have been confined to the identification of hormonal and psychological markers of overtraining and fatigue. In addition, studies examining the influence of training load on injury in collision sports have been limited to subelite athletes (21). In the elite team-sport environment, it is critical to have the maximum number of players free from injury and available for selection in as many games as possible throughout the season (34,36). Injuries that result in lost playing time may alter the team structure, leading to reduced cohesion between players, and subsequent reductions in playing performance (16). However, to date, limited information exists on the training dose–response relationship in elite collision sport athletes. In addition, no study has developed an injury prediction model for collision sport athletes. With this in mind, the purpose of this study was to develop an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes.

METHODS

Experimental Approach to the Problem

This study involved (a) the collection of training load and noncontact, soft-tissue injury data (over 2 competitive seasons); (b) the modeling of training load with injury, to determine the relationship between these 2 variables (i.e., with a given training load, what is the risk of noncontact, soft-tissue injury?); and (c) the development and application of an injury prediction model encompassing planned and actual training loads (over a subsequent 2 seasons). The study was conducted in 2 phases: Firstly, training load and injury data were prospectively recorded over 2 competitive seasons in elite collision sport athletes. Training load and injury data were modeled using a logistic regression model with a binomial distribution (injury vs. no injury) and logit link function. This model was identical to that previously used to investigate the training–injury relationship in subelite collision sport athletes (21). The development of this model provided statistical information on the likelihood of soft-tissue injury with a given training load, throughout the different phases of the season (i.e., preseason, early competition, late competition). Secondly, training load and injury data were prospectively recorded over a further 2 competitive seasons in the same cohort of elite collision sport athletes. Based on the results of the logistic regression model, an injury prediction model encompassing planned and actual training loads was developed and implemented to determine if noncontact, soft-tissue injuries could be predicted and therefore prevented in elite collision sport athletes. The proportion of true positive (i.e., predicted injury and player sustained injury) and negative (i.e., no injury predicted and the player did not sustain injury) results, and false positive (i.e., predicted injury but the player did not sustain any injury) and negative (i.e., no injury predicted but the player sustained an injury) results were also calculated to describe errors made in the statistical decision process and to allow the calculation of sensitivity (i.e., the proportion of injured players who were predicted to be injured) and specificity (i.e., the proportion of uninjured players who were predicted to remain injury-free) likelihood ratios (1).

Subjects

Ninety-one professional rugby league players (mean ± *SD* age, height, and body mass; 23.7 ± 3.8 years, 183.2 ± 4.9 cm, and 94.4 ± 9.2 kg, respectively) participated in this 4-year prospective study (2006–2009). Of the 91 players, 53 (58.2%) played 1 season, 22 players (24.2%) played 2 seasons,

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7 players (7.7%) played 3 seasons, whereas 9 players (9.9%) played all 4 seasons. The number of players participating in each season was 36, 38, 35, and 45 respectively, giving a total of 154 player seasons. All players were highly motivated players from the same professional rugby league club and were competing in the elite National Rugby League competition. Players had completed a 4-week active recovery off-season period and were free from injury at the commencement of the study. All players received a clear explanation of the study, including the risks and benefits of participation, and written consent was obtained. The Institutional Review Board for Human Investigation approved all experimental procedures.

Data Collection

This study was conducted in 2 phases: Firstly, training load and injury data were prospectively recorded over 2 competitive seasons (2006 and 2007). Training load and injury data were modeled to determine the relationship between training load and the likelihood of injury (21). Secondly, training load and injury data were prospectively recorded over a further 2 competitive seasons (2008 and 2009). During this period, an injury prediction model based on planned and actual training loads was developed and implemented to determine if noncontact, soft-tissue injuries could be predicted and therefore prevented in elite collision sport athletes.

Training Sessions

A periodized, game-specific training program was implemented, with training loads progressively increased in the general preparatory phase of the season (i.e., November to February) and reduced during the competitive phase of the season (i.e., March to October). The training program progressed from high volume–low intensity activities during the preseason conditioning period to low volume–high intensity activities during the in-season conditioning period. Each player participated in up to 5 organized field-training sessions, and 4 strength sessions per week in the preseason period, and 2–4 field-training sessions, and 1–2 strength sessions per week in the competitive phase of the season. Training load and injury data were recorded for every session.

To ensure training specificity, players were allocated into 1 of 3 training groups (i.e., hit-up forwards, adjustables, and outside backs) according to the skills and physiological demands of their individual positions. The content of sessions was based largely on perceived strengths and weaknesses within the club. The training sessions consisted of specific skills, speed, muscular power, agility, and endurance training common to rugby league. Skills sessions were designed to develop passing and catching skills, defensive line speed and technique, support play, and ball control. Although some differences existed in the intensity of activities performed throughout the season, the types of activities performed in the preseason training phase (e.g., basic skills, light and full contact tackling drills and longer interval running) were similar to the early-competition and late-competition training phases (e.g., light contact tackling drills, advanced skills, and shorter repeated-sprint training). The duration of training sessions was recorded, with sessions typically lasting between 60 and 120 minutes. An outline of the training plan for the season is shown in Table 1.

Quantification of Training Loads

The intensity of individual training sessions was estimated using a modified rating of perceived exertion (RPE) scale (13). Training load was calculated by multiplying the training session intensity by the duration of the training session and was reported in arbitrary units. Intensity estimates were obtained 30 minutes after completing the training session. When compared to heart rate and blood-lactate concentration, the RPE scale has been shown to provide a valid estimate of exercise intensity (8,10,27). In addition, before commencing the study, we investigated the relationship between heart rate and RPE, and blood-lactate concentration and RPE on a subset of subjects during typical rugby league training activities. The correlations between training heart rate and training RPE, and training blood-lactate

Table 1. Outline of yearly training plan for elite collision sport athletes.*

Training phase	Objective
Preseason	Develop speed, agility, and muscular power Develop aerobic endurance, anaerobic capacity, and repeated-effort ability Develop game-specific individual and team skills
Early-competition	Continue to develop game-specific skills Maintain aerobic endurance, anaerobic capacity, repeated-effort ability, speed, agility, and muscular power
Late-competition	Maintain game-specific skills Maintain aerobic endurance, anaerobic capacity, repeated-effort ability, speed, agility, and muscular power

*Preseason = 16 weeks; early-competition = 15 weeks; late-competition = 15 weeks.

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concentration and training RPE, were 0.89 and 0.86, respectively (21). A subset of players ($n = 11$) also completed 2 identical off-season training sessions, performed 1 week apart, before the commencement of the study, to determine test–retest reliability. The intraclass correlation coefficients for test–retest reliability and typical error of measurement for the RPE scale were 0.99 and 4.0%, respectively. Collectively, these results demonstrate that the RPE scale offers an acceptable method of quantifying training intensity for collision sport athletes.

Definition of Injury

For the purpose of this study, an injury was defined as any noncontact, soft-tissue injury sustained by a player during a training session or match that prevented the player from completing the entire training session or match (17). To allow comparisons among seasons, injuries were also classified according to matches missed as a result of the injury (22). All contact injuries were excluded from the analysis.

Statistical Analyses

Differences in training loads among the preseason, early-competition, and late-competition training phases and between the 2006–2007 and 2008–2009 seasons were analyzed using a 2-way (season × training phase) analysis of variance with repeated measures. Injury exposure was calculated by multiplying the number of players by the session duration. Injury incidence was calculated by dividing the total number of injuries by the overall injury exposure.

Influence of Training Load on Likelihood of Injury. The training load and injury data collected in the first 2 seasons were modeled to provide the likelihood of soft-tissue injury with a given training load. Individual training load and injury data were modeled using a logistic regression model with a binomial distribution (injury vs. no injury) and logit link function. Data were analyzed in SAS using the PROC GENMOD procedure. This procedure was used based on its ability to handle logistic regression. PROC GENMOD also has the ability to handle unbalanced models (where different numbers of repeated results were available for each player). The summary statistic used for assessing the adequacy of the fitted logistic model (goodness of fit) was the scaled deviance of the model and significance of independent variables. A scaled deviance of 1 refers to a perfect fit. Based on the distribution of the training load data and the scaled deviance, it was also determined that the model was best fitted with the log of the training load per week. This model was also chosen as an identical model had been validated and used previously to investigate the training–injury relationship in subelite collision sport athletes (21).

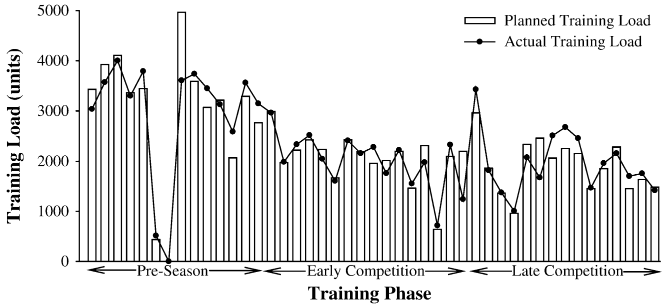

Figure 1. Weekly planned and actual training loads for the preseason, early-competition, and late-competition training phases in elite collision sport athletes.

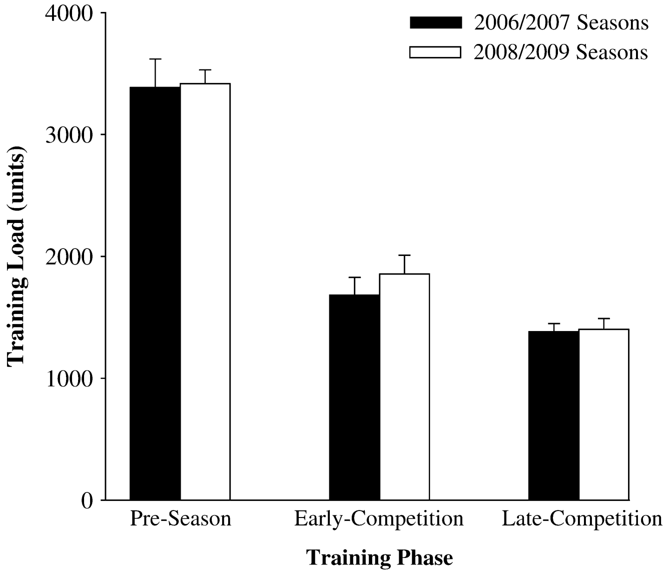

Figure 2. Preseason, early-competition, and late-competition training loads for the 2006–2007 and 2008–2009 seasons in elite collision sport athletes.

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Table 2. Site and type of injuries resulting in missed matches for the 2006–2007 and 2008–2009 seasons.*†

	2006–2007 Season			2008–2009 Season		
	Number	Injury rate	%	Number	Injury rate	%
Site						
Thorax/abdomen	6	0.5 (0.1–0.8)	20.0	2	0.2 (0.0–0.4)	7.7
Anterior thigh	6	0.5 (0.1–0.8)	20.0			
Posterior thigh	12	0.9 (0.4–1.4)	40.0	10	0.8 (0.3–1.2)	38.5
Groin				2	0.2 (0.0–0.4)	7.7
Knee	6	0.5 (0.1–0.8)	20.0	9	0.7 (0.2–1.1)	34.6
Calf				3	0.2 (0.0–0.5)	11.5
Type						
Muscular strains	24	1.8 (1.1–2.6)	80.0	17	1.3 (0.7–1.9)	65.4
Overuse	4	0.3 (0.0–0.6)	13.3	6	0.5 (0.1–0.8)	23.1
Joint sprains	2	0.2 (0.0–0.4)	6.7	3	0.2 (0.0–0.5)	11.5
Total	30	2.3 (1.5–3.1)	100.0	26	2.0 (1.2–2.8)	100.0

*The number and incidence of injuries represents any noncontact, soft-tissue injury that resulted in a missed match.
†Injury rates are expressed per 1,000 exposure hours (and 95% confidence intervals).

Injury Prediction Model. Based on the results of the logistic regression model, an injury prediction model encompassing planned and actual training loads was developed and implemented to determine if noncontact, soft-tissue injuries could be predicted and therefore prevented. Differences in planned and actual training loads throughout the season were analyzed using Cohen's effect size (ES) statistic. Effect sizes of 0.2, 0.5, and 0.8 were considered small, moderate, and large, respectively (7). A moderate difference (i.e., ES of 0.5) between the planned and actual training load was required for the 'threshold' training load to be exceeded. Effect sizes were calculated by multiplying the between-subject *SD* for training load by 0.5 (7). Given that a relationship was identified between training load and injury (from the first 2 seasons), it was possible to plan training loads to minimize the effect of injuries. When actual training loads for individual players were higher (based on a moderate ES) than planned training loads, then judgments were made on the individual management of the player (e.g., players continued to train without modifications, or training loads for those individual players were modified, or reduced to minimize the risk of injury). Injury prevalence was calculated as the proportion of players injured when actual training loads exceeded planned training loads.

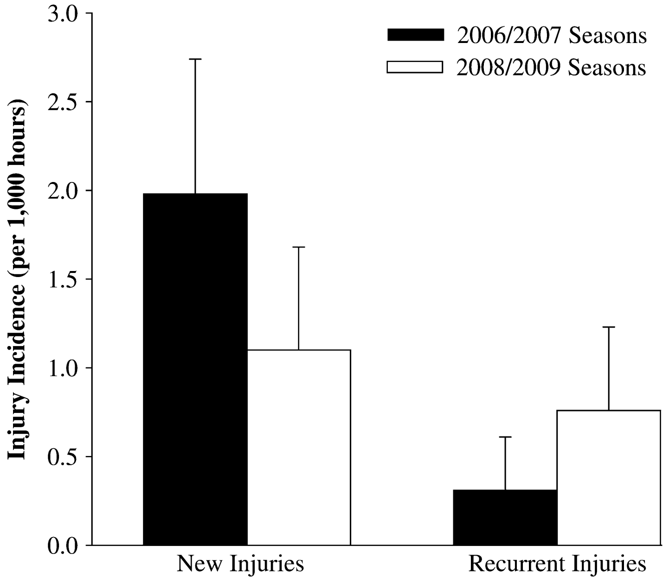

Figure 3. Incidence of new and recurrent injuries for the 2006–2007 and 2008–2009 seasons in elite collision sport athletes. The incidence of injuries represents any noncontact, soft-tissue injury that resulted in a missed match.

Sensitivity and Specificity of the Injury Prediction Model. Data were crossvalidated to determine

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the accuracy of the injury prediction model. The proportion of true positive (i.e., predicted injury and player sustained injury) and negative (i.e., no injury predicted and the player did not sustain an injury) results, and false positive (i.e., predicted injury but the player did not sustain any injury) and negative (i.e., no injury predicted but the player sustained an injury) results were also calculated to describe errors made in the statistical decision process and to allow the calculation of sensitivity (i.e., the proportion of injured players who were predicted to be injured) and specificity (i.e., the proportion of uninjured players who were predicted to remain injury-free) likelihood ratios (1). Sensitivity and specificity values were calculated using the following equations:

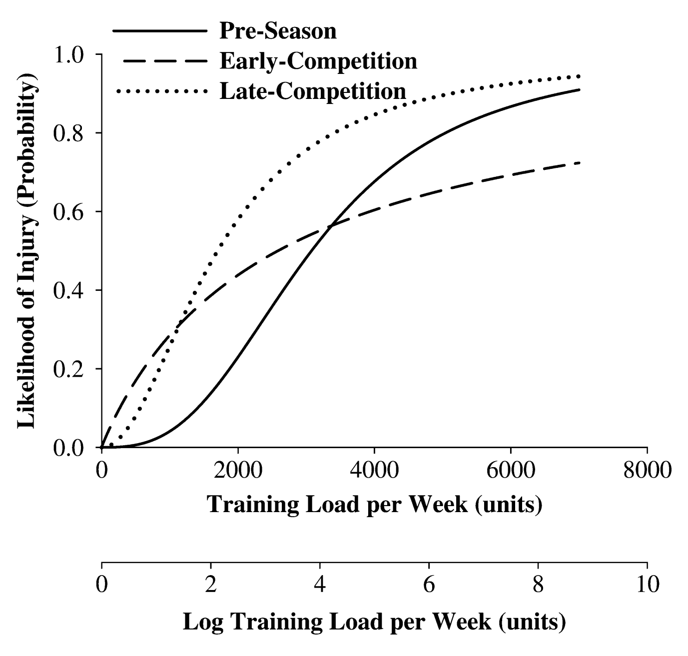

Figure 4. Relationships between training load, training phase, and likelihood of injury in elite collision sport athletes.

$$\text{Sensitivity} = \text{True Positive}/(\text{True Positive} + \text{False Negative}),$$

$$\text{Specificity} = \text{True Negative}/(\text{False Positive} + \text{True Negative}).(1)$$

Positive and negative likelihood ratios were calculated using the following equations:

$$\text{Likelihood ratio positive} = \text{Sensitivity}/(1 - \text{Specificity}),$$
$$\text{Likelihood ratio negative} = (1 - \text{Sensitivity})/\text{Specificity}.(1)$$

Although there were 91 players in the sample, injury predictions based on the training loads performed by individual players were made on a weekly basis, so that within the total cohort, there was a total number of true positive and negative predictions, and a total number of false positive and negative predictions. Data are expressed as means and 95% confidence intervals (CIs), and the level of significance was set at $p \leq 0.05$.

RESULTS

Training Loads

The planned and actual training loads for the preseason, early-competition, and late-competition training phases are shown in Figure 1. The preseason training loads were greater than the early-competition and late-competition training loads.

Comparison of Training Loads between Seasons

No significant differences ($p > 0.05$, ES = 0.03–0.30) were detected in training loads for the 2006–2007 and 2008–2009 preseason, early-competition, or late-competition training phases (Figure 2).

TABLE 3. Actual training loads of injured players, and the corresponding prevalence of noncontact, soft-tissue injury.*†

	Preseason	Early competition	Late competition
Training load (units)	4,341 (4,082–4,600)	3,395 (3,297–3,493)	2,945 (2,797–3,094)
Injury prevalence (%)	72 (63–81)%	57 (47–67)%	75 (66–84)%

*Injury prevalence = proportion of players injured when actual training loads exceeded planned training loads. †Data are expressed as means (and 95% confidence intervals).

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TABLE 4. Site and type of predicted injuries during the 2008–2009 season.*†

Site	Number	Injury rate	%	Type	Number	Injury rate	%
Thorax	2	0.2 (0.0–0.4)	1.2	Muscular strains	110	8.4 (6.8–10.0)	68.3
Lumbar	8	0.6 (0.2–1.0)	5.0	Overuse	48	3.7 (2.6–4.7)	29.8
Anterior thigh	13	1.0 (0.5–1.5)	8.1	Joint sprains	1	0.1 (0.0–0.2)	0.6
Posterior thigh	57	4.4 (3.2–5.5)	35.4				
Groin	22	1.7 (1.0–2.4)	13.7				
Knee	25	1.9 (1.2–2.7)	15.5				
Calf	21	1.6 (0.9–2.3)	13.0				
Foot	10	0.8 (0.3–1.2)	6.2				
Other	1	0.1 (0.0–0.2)	0.6				
Total	159	12.1 (10.2–14.0)	100.0	Total	159	12.1 (10.2–14.0)	100.0

*The number and incidence of injuries represent any noncontact, soft-tissue injury that prevented the player completing the entire training session or match.

†Injury rates are expressed per 1,000 exposure hours (and 95% confidence intervals).

Incidence of Missed Match Injuries over the 4 Seasons

Site and Type of Missed Match Injuries. Players participated in 13,103 exposure hours over both the 2006–2007 and 2008–2009 seasons (for a total of 26,206 exposure hours). Of the 80 contracted players in the 2008–2009 seasons, 49 (61.3%) sustained at least 1 noncontact, soft-tissue injury. Of the players who sustained an injury, 35 (71.4%) sustained 2 or more injuries. The majority of missed match injuries sustained over the 4 seasons were to the posterior thigh (0.8 [95% CI, 0.5–1.2] per 1,000 hours, 39.3%). Muscular strains were the most common type of injury (1.6 [95% CI, 1.1–2.0] per 1,000 hours, 73.2%) (Table 2).

Comparison of Missed Match Injuries between Seasons

The total number of missed match injuries in the 2006–2007 and 2008–2009 seasons was 30 and 25, respectively. The incidence of soft-tissue injury resulting in a missed match was 2.3 (95% CI, 1.5–3.1) per 1,000 hours and 1.9 (95% CI, 1.2–2.7) per 1,000 hours for the 2006–2007 and 2008–2009 seasons, respectively. Although not significant ($p > 0.05$), the incidence of new injuries was greater in the 2006–2007 seasons (2.0 [95% CI, 1.2–2.8] per 1,000 hours vs. 1.1 [95% CI, 0.6–1.7] per 1,000 hours), whereas the incidence of recurrent injuries was greater in the 2008–2009 seasons (0.3 [95% CI, 0.0–0.6] per 1,000 hours vs. 0.8 [95% CI, 0.3–1.2] per 1,000 hours) (Figure 3).

TABLE 5. Accuracy of model for predicting noncontact, soft-tissue injuries.*†

		Actual status	
		Injured	Not injured
Predicted status	Predicted injury	True positive $N = 121$	False positive $N = 20$
	Predicted no injury	False negative $N = 18$	True negative $N = 1589$
		Sensitivity 87.1 (80.5–91.7)%	Specificity 98.8 (98.1–99.2)%
		Likelihood ratio positive 70.0 (45.1–108.8)	
		Likelihood ratio negative 0.1 (0.1–0.2)	

*True positive = predicted injury and player sustained injury; false positive = predicted injury but player did not sustain injury; false negative = no injury predicted but player sustained injury; true negative = no injury predicted and player did not sustain injury; sensitivity = proportion of injured players who were predicted to be injured; specificity = proportion of uninjured players who were predicted to remain injury-free; Likelihood ratio positive = sensitivity/(1 − specificity); likelihood ratio negative = (1 − sensitivity)/specificity.

†Although there were 91 players in the sample, injury predictions based on the training loads performed by individual players were made on a weekly basis, so that within the total cohort, there was a total number of true positive and negative predictions, and a total number of false positive and negative predictions. Sensitivity and specificity data and positive and negative likelihood ratios are expressed as rates (and 95% confidence intervals).

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Influence of Training Load on Likelihood of Injury

Based on the results of the logistic regression model, players were 50–80% likely to sustain a preseason injury within the training load range of 3,000–5,000 units. These training load 'thresholds' were considerably reduced (1,700–3,000 units) in the late-competition phase of the season (Figure 4). The actual preseason, early-competition, and late-competition training loads performed by injured players were 4,341 (95% CI, 4,082–4,600), 3,395 (95% CI, 3,297–3,493), and 2,945 (95% CI, 2,797–3,094) units, respectively. When actual training loads for individual players were higher than planned training loads, noncontact, soft-tissue injury occurred in 72 (95% CI, 63–81), 57 (95% CI, 47–67), and 75 (95% CI, 66–84)% of cases, for the preseason, early-competition, and late-competition training phases, respectively (Table 3).

Injury Prediction Model

Site and Type of Predicted Injuries. A total of 159 noncontact, soft-tissue injuries were sustained over the latter 2 seasons (2008–2009). The majority of injuries predicted in the 2008–2009 seasons were to the posterior thigh (4.4 [95% CI, 3.2–5.5] per 1,000 hours, 35.4%). Muscular strains were the most common type of injury (8.4 [95% CI, 6.8–10.0] per 1,000 hours, 68.3%) (Table 4).

Sensitivity and Specificity of the Injury Prediction Model

The percentage of true positive predictions was 62.3% ($n =$ 121), whereas the total number of false positive and false negative predictions was 20 and 18, respectively. The sensitivity and specificity of the injury prediction model were 87.1 (95% CI, 80.5–91.7)% and 98.8 (95% CI, 98.1–99.2)%, respectively (Table 5). The calculated positive and negative likelihood ratios were 70.0 (95% CI, 45.1–108.8) and 0.1 (0.1–0.2), respectively.

DISCUSSION

The present study is the first to describe an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes. The use of the injury prediction model allowed medical staff to make informed decisions on training management on a scientific basis, whereas modeling of training load and injury data identified the training load ranges that resulted in an "acceptable" injury risk and also the training load ranges that resulted in an "unacceptable" injury risk. These findings provide a scientific method of monitoring and regulating training load that removes the 'guesswork' from training.

Previous studies of collision sport athletes have reported a significant relationship ($r = 0.86$) between training loads and training-injury rates (17), suggesting that the harder these athletes train, the more injuries they will sustain. Furthermore, reductions in training loads have been shown to reduce training-injury rates and result in greater improvements in $\dot{V}O_2$max (18). However, it has also been shown that collision sport athletes that perform <18 weeks of preseason training before sustaining an initial injury are at increased risk of sustaining a subsequent injury, whereas players with a low off-season $\dot{V}O_2$max are at increased risk of sustaining a contact injury (20). Clearly, training for collision sports reflects a balance between the minimum training load required to elicit an improvement in fitness and the maximum training load tolerable before sustaining marked increases in injury rates. In the elite team sport environment, it is critical to have the maximum number of players free from injury and available for selection in as many games as possible throughout the season (34,36). The developed injury prediction model provides a practical framework to monitor training loads and prevent noncontact, soft-tissue injuries in elite collision sport athletes.

Modeling of training load and injury data of players identified safe and unsafe training loads for different phases of the season. In the preseason training period, players were 50–80% likely to sustain an injury within the training load range of 3,000–5,000 units. However during the late-competition phase, significantly less training could be tolerated before increasing the likelihood of injury; players were 50–80% likely to sustain an injury within the training range of 1,700–3,000 units. In all 3 training phases (preseason, early-competition, and late-competition), small increases in training load resulted in large increases in injury likelihood. Indeed, when actual training loads for individual players were higher than planned training loads, noncontact, soft-tissue injury occurred in 72, 57, and 75% of cases, for the preseason, early-competition, and late-competition training phases, respectively. Collectively, these results give practical information on the training–injury dose–response relationship in elite collision sport athletes.

Players that exceeded the training load threshold were 70 times more likely to test positive for noncontact, soft-tissue injury, whereas players that did not exceed the training load threshold were injured 1/10 as often. These results demonstrate that the developed model was adequately sensitive to detect both players who were susceptible to noncontact, soft-tissue injuries and players who were not susceptible to injury. It should be emphasized that in 62.3% of cases, a player was highlighted as having the potential for injury and no intervention was undertaken (and the player was subsequently injured). These results compare favorably with the proportion of players (11.3%) who sustained a soft-tissue injury despite not being predicted as being at risk for soft-tissue injury. Although there are numerous examples of highly skilled individuals using 'intuition' to identify potential problems within their area of expertise (25), the present findings suggests that the information generated from training monitoring could have been used more efficiently. Despite the additional scientific information generated by the injury prediction model, strength and conditioning coaches were more comfortable using their intuitive 'expertise' to manage the training loads of players. Unfortunately, the model had far greater accuracy predicting injuries (62.3%)

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than it did influencing the decision making of strength and conditioning staff, with <14% of players provided alternative training or additional recovery when an injury was predicted. It is likely that a combination of intuitive 'expertise' and the injury prediction model may have provided greater accuracy in predicting training-related, soft-tissue injuries (38,40). Given the success in predicting injuries and that the total proportion of incorrect predictions was small (23.9%), these results suggest that the injury prediction model provides greater sensitivity than the sole judgment of strength and conditioning staff.

No significant differences existed between the initial 2 seasons (where no injury prediction model was used) and latter 2 seasons (where the injury prediction model was developed and implemented) for the incidence of missed match injuries. These findings may be attributed to the similar training loads employed in the initial and latter seasons. However, it is also possible that the failure to reduce noncontact, soft-tissue injuries with the introduction of the injury prediction model was because of the low overall incidence of missed match soft-tissue injuries over this period. Indeed, the soft-tissue injury rates reported in this study are considerably lower than other running-based team sports (e.g., Australian football) (35). It is therefore likely that a training monitoring model designed to capture training load-related soft-tissue injuries may have better application to team sports with a greater emphasis on running, and a lower emphasis on physical collisions. Indeed, team sports such as Australian football, basketball, and soccer, which typically employ high running loads to condition players, would likely benefit more from the developed injury prediction model than collision sports that have a greater emphasis on conditioning through physical contact (e.g., American football). Nonetheless, the present findings demonstrate the applicability of an injury prediction model to detect noncontact, soft-tissue injuries in elite collision sports that incorporate high volumes and intensities of both physical contact and running into their conditioning programs.

It should be noted that the injury prediction model has a number of potential limitations. Firstly, the developed model is unable to predict collision injuries. However, although collision injuries are multifactorial, it is likely that players with better developed physical qualities may be less susceptible to collision injuries, whereas overtrained players may be at a greater risk of injury. Indeed, several rugby league studies have reported a significant relationship ($r = 0.86$) between training loads and training-injury rates (17), suggesting that the harder these athletes train, the more injuries they will sustain. Furthermore, although limited evidence exists in elite collision sport athletes, previous studies on subelite collision sport athletes have shown that performing <18 weeks of preseason training before sustaining an initial injury increases the risk of sustaining a subsequent injury, whereas players with a low off-season $\dot{V}O_2$max are at an increased risk of sustaining a contact injury (20). Secondly, the accuracy of the model for predicting training load-related soft-tissue injuries is dependent on the quality of data entered. In the present study, training loads were estimated from the session-RPE, a subjective measurement of training load. Future injury prediction models could include global positioning system data, data on the number and intensity of collisions, markers of fatigue (e.g., self-reports, neuromuscular and hormonal data), and match work rates to further refine the present training monitoring system. Finally, although the model was successful in predicting injuries over 2 competitive seasons, its continued success is dependent on knowledge of planned and actual training loads. Planned training loads for conditioning, strength, and skill sessions are required for the injury prediction model to operate effectively.

Although the injury prediction model used in this study had sufficient predictive accuracy to warrant systematic use in an elite team sport program, a fine balance exists between training, detraining, and overtraining. Furthermore, although a relationship was observed between training load and likelihood of injury, training programs must also be physiologically efficient and psychologically appropriate to allow players to cope with the demands of competition (6). Indeed, exposing the brain to hard physical work and fatigue on a regular basis appears to improve the body's ability to cope with fatigue; physically intense training not only improves physical fitness but equally importantly also increases the mental durability of players (33). Physically (and mentally) unfit players are more likely to pace themselves as a self-preservation and protection strategy (33). If players have not been exposed to hard physical work on a regular basis, the brain instructs the body to stop exercise earlier to prevent exhaustion (33). With this in mind, it may be argued that it is worthwhile prescribing high training loads (note, not excessive) to players to determine which players are most susceptible to injury under physically stressful situations (these players most likely will not tolerate the intensity and fatigue of competition), and which players are not susceptible to injury under physically stressful situations (these players are more likely to tolerate the intensity and fatigue of competition).

In conclusion, this study developed an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes. Players that exceeded the training load threshold were 70 times more likely to test positive for noncontact, soft-tissue injury, whereas players that did not exceed the training load threshold were injured 1/10 as often. Modeling of training load and injury data identified the training load ranges that resulted in an "acceptable" injury risk and also the training load ranges that resulted in an "unacceptable" injury risk. From a practical perspective, these findings provide information on the training dose–response relationship, and a scientific method of monitoring and regulating training load in elite collision sport athletes.

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PRACTICAL APPLICATIONS

There are several practical applications of this study that are relevant to the strength and conditioning coach. Monitoring and regulating training loads is critical to ensure that players receive a progressively overloaded periodized training program and are given adequate recovery between high-volume and high-intensity sessions. It is important for strength and conditioning coaches to work closely with sport scientists to determine the appropriate training and recovery periods to maximize improvements in performance without unduly increasing injury incidence.

Players that exceeded the training load threshold were 70 times more likely to test positive for noncontact, soft-tissue injury, whereas players that did not exceed the training load threshold were injured 1/10 as often. In 62.3% of cases, a player was highlighted as having the potential for injury, and no intervention was undertaken (and the player was subsequently injured). Given the success in predicting injuries, and that only a small proportion (23.9%) of incorrect predictions were made, these results suggest that the injury prediction model provides greater sensitivity than the sole judgment of strength and conditioning staff. Indeed, a large proportion of injuries may have been prevented if strength and conditioning staff heeded the warnings provided through the scientific analysis of the training loads.

Finally, although the injury prediction model provided a successful framework to manage noncontact, soft-tissue injuries it should be recognized that the model was based on planned and actual training loads. An assumption with this model is that players possess adequate physical qualities to perform rigorous physical training and that the planned training loads were adequate to develop and maintain physical fitness. To some extent, this framework constrains the amount of physical adaptation permitted through training, by limiting the amount of physical work that can be performed. Allowing players to exert themselves above and beyond the planned training loads may result in soft-tissue injury but could also produce greater physical adaptations and mental durability in players.

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