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The Magnitude of Translational and Rotational Head Accelerations Experienced by Riders During Downhill Mountain Biking

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Abstract

Objectives

To determine the magnitude of translational and rotational head accelerations during downhill mountain biking.

Design

Observational study

Methods

Sixteen male downhill cyclists (age 26.4 ± 8.4 years; stature 179.4 ± 7.2 cm; mass 75.3 ± 5.9 kg) were monitored during two rounds of the British Downhill Series. Riders performed two runs on each course wearing a triaxial accelerometer behind the right ear. The means of the two runs for each course were used to determine differences between courses for mean and maximum peak translational (g) and rotational accelerations (rads/s^2) and impact duration for each course.

Results

Significant differences ($p < 0.05$) were revealed for the mean number of impacts (>10 g), FW = 12.5 ± 7.6, RYF = 42.8 ± 27.4 ($t_{(22.96)} = -4.70$; $p < 0.001$; 95 % CI = 17.00 to 43.64); maximum peak rotational acceleration, FW = 6805.4 ± 3073.8 rads/s^2, RYF = 9799.9 ± 3381.7 rads/s^2 ($t_{(32)} = -2.636$; $p = 0.01$; 95 % CI = 680.31 to 5308.38); mean acceleration duration FW = 4.7 ± 1.2 ms, RYF = 6.5 ± 1.4 ms ($t_{(32)} = -4.05$; $p < 0.001$; 95 % CI = 0.91 to 2.76) and maximum acceleration duration, FW = 11.6 ± 4.5 ms, RYF = 21.2 ± 9.1 ($t_{(29.51)} = -4.06$; $p = 0.001$; 95 % CI = 4.21 to 14.94). No other significant differences were found.

Conclusions

Findings indicate that downhill riders may be at risk of sustaining traumatic brain injuries and course design influences the number and magnitude of accelerations.

Keywords: Injury; brain; concussion; accelerometry; mountain biking.

1. Introduction

Concussion can occur when there is any blow directly to the head, neck, face or body, resulting in an impulsive force transmitted to the head causing intracranial trauma[1]. To date, the majority of information relating to head injuries in sports relates to team games, notably rugby, soccer, gridiron and ice hockey. However, events such as motocross, BMX and mountain biking (MTB) see participants compete on irregular surfaces, leading to repeated translational and rotational accelerations of the head, which may potentially influence athlete health. Downhill mountain biking (DHI) requires competitors to perform timed runs down an off road track, with race times typically ranging between 2 and 5 minutes over a course length between 1.5 and 3.5 km[2].

Courses generally consist of a combination of fast open hillside trails and technical forestry sections, and include obstacles such as rock gardens, jumps, vertical drops and roots. As such the emphasis of DHI is predominantly on technical skills rather than physical fitness[3].

Whilst there has been an increase in DHI research in recent years, such research has focused primarily on the performance demands of the sport[4,5]. However, given the high velocities reported during DHI (>25 km.h^{-1})[5] and the technical nature of tracks, the potential for falls and subsequent impact injuries is elevated. Despite such risks, information relating to the epidemiology of injuries sustained during DHI is limited.

Of the published data available, Kronisch et al. (1996)[6] reported 20 injuries out of 4074 participants in cross-country (XCO) mountain biking and only 11 injuries from 2158 participants in DHI over three races at the 1995 NORBA mountain bike series in the USA. Of these, concussions equated to 13 % of all injuries reported. A survey on injuries in DHI during the 2011 European competition season reported a total of 494 different injuries sustained by the 249 respondents to the survey. Of these injuries, 23 concussions were reported, accounting for 5 % of all injuries[7]. Data based on the International Ski Federation (FIS) Injury Surveillance System (ISS) found head injuries to account for 8-10 % of all reported injuries at World Cup level[8]. This is comparable to rates previously reported for MTB.

The magnitude of head accelerations resulting from trail vibrations has not yet been established. However, research on head accelerations in youth BMX riders between 6-18 years of age found mean rotational loads were between 1440.7 and 1951.8 rads/s^2, whilst mean peak translational load was between 23.2 and 29.6 g across the age ranges[9]. Individual peak translational loads between 70 and 133 g and peak rotational loads between 12,000 and 14,000 rads/s^2 were observed. Mean peak translational loads have also been shown to be greater in magnitude than those in many contact sports[10]. Mean peak translational loads of 25 g have been reported for male youth soccer players[10] and approximately 12 g in collegiate female soccer players[11]. However, unlike DHI, BMX is performed on relatively smooth hard packed dirt, concrete or tarmac tracks. Therefore, head impacts during DHI may be much larger than those observed for BMX.

Several studies have attempted to establish head impact velocities during alpine and freestyle skiing and snowboarding accidents[12,13]. These studies typically found linear head velocity pre-impact to be ~8 m/s and ~10 m/s upon impact. Scher et al[14] reported peak linear accelerations of 83 g and 162 g during snowboarding back edge catches when helmeted. However, a major limitation of these studies is the use of video footage and motion analysis software or Hybrid III anthropomorphic test devices (dummies) to predict impact velocities. Therefore, they may be subject to errors in camera alignment, camera blurring and snow spray, whilst dummies do not react in the same manner as humans in the event of an accident. Additionally, these studies looked at direct contacts between the head and ground and did not report head accelerations due to course terrain without crashing.

Peak head accelerations of the magnitude reported for BMX and contact sports have the potential for decreasing cognitive function. Accelerations as low as 33 g have been shown to impair cognition and white matter integrity in athletes participating in contact sports[15]. Additionally, proposed thresholds for the occurrence of mild traumatic brain injury (mBTI's) have estimated maximum translational acceleration to be 66, 82 and 106 g for a 25, 50 and 80 % probability of sustaining a mTBI[16]. Additionally, previous research has also proposed that head accelerations with a duration of 15 ms or less were more critical to sustaining a concussion[17].

Classifying head accelerations that do not result in concussion is often referred to as within the sub-concussive threshold[18]. Whilst these sub-concussive events may not manifest as an identifiable concussion, there is emerging evidence that they can cause damage to the central nervous system and assist in the accumulation of translational and rotational acceleration forces to the brain[19,20]. Given the potential role of accumulating sub-concussive accelerations in changing the pathophysiology of the brain[20,21] and allied neuropsychology[22] profiling of such events is surprisingly limited. Therefore, the aim of this study was to determine the magnitude of translational and rotational head accelerations during DHI riding on two different courses and whether these differ by course. Based on previous research, it was hypothesised that the acceleration variables would differ between courses and values be greater than those observed for other cycling disciplines due to the nature of the terrain involved.

2. Methods

Sixteen male competitive DHI cyclists (age 26.4 ± 8.4 years; stature 179.4 ± 7.2 cm; mass 75.3 ± 5.9 kg) participated in the study. The sample was comprised of riders across different race categories (Elite n = 6; Elite Juniors n = 3; Seniors n = 5; and Masters n = 2), with all riders having a minimum of 4 years racing experience at National or International level. All participants had raced previously at the chosen venues. Participants provided written and informed consent prior to taking part in the study, which was granted ethical approval by the University of Central Lancashire STEMH ethics committee and was in accordance with the principles outlined in the Declaration of Helsinki.

Data collection was conducted at two rounds of the 2017 British Downhill Series. The first session took place at the Fort William (FW) round in Scotland (course length = 2.82 km; start altitude = 655 m vertical drop = 555 m). The second session took place at the Rhyd-y-Felin (RYF) round in Wales (course length = 1.5 km; start altitude = 543 m; vertical drop = 367 m). Both courses typically comprised of fast open forestry/moorland tracks and technical wooded sections. These courses were also chosen specifically, as they represented the longest and shortest tracks of the 2017 series and FW is a faster less technical course, whilst RYF is more technically demanding.

Each rider was fitted with a triaxial accelerometer (xPatch, X2 Biosystems, Seattle, USA) in order to determine the number of accelerations for each run and the mean peak and maximum peak translational (g) and rotational (rads/s^2) accelerations of the head and mean and maximum acceleration durations. The sensors were positioned behind the right ear at the level of the occipito-temporal suture (Fig.1). Translational accelerations were sampled at 1000 Hz, whilst rotational accelerations were sampled at 800 Hz. An ‘acceleration’ was defined as any event >10 g for translational acceleration. The accelerometers had been previously validated for accelerations up to 160 g[23]. Therefore, recorded values above or below the minimum and maximum thresholds were deemed erroneous and removed from the dataset. All riders performed each run on their own full suspension downhill mountain bike and set suspension and tyre pressure to their personal preference for each course. As per governing body regulations, each rider wore a full-face motocross style helmet and full finger bicycle gloves during each run as a minimum protective equipment.

All data collection were performed during the timed practice sessions. Following placement of the sensors, riders were free to practice the course in the morning for 3 hours. During this time, riders performed between 3 and 5 runs of the courses and were free to stop on course to determine optimal line choices for the race. Following this, riders recovered passively for 1 hour prior to the afternoons timed practice session. During this session each rider performed 2 full runs as quickly as possible without stopping on each course. The mean of the two runs for each course was determined and used for analysis of differences between courses. Separate sensors were used for each run.

As different riders were tested at each event, differences between courses were determined using independent t-tests, whilst the study also presents descriptive data for each course and overall. When data from the two courses were combined, differences were established between race categories using a between groups one-way analysis of variance (ANOVA). Bonferroni *post hoc* analyses were used to determine where significant differences lay. Effect sizes were calculated using a partial Eta^2 (η_p^2) and classified as small (0.01), medium (0.09) and large (>0.25)[24]. All data were analysed using SPSS 23 (SPSS inc., Chicago, IL, USA) and are presented as mean ± standard deviation (95 % CI) and median. Statistical significance was accepted at the alpha level $p \leq 0.05$.

3. Results

Times for timed practice sessions were not made public. However, mean race times were 5:41 ± 1:07 min:s for FW and 3:15 ± 0:65 min:s for RYF. Significant differences existed between race times ($t_{(10.69)} = 5.29$; $p < 0.001$; 95 % CI = 1.32 to 3.20). Over the two timed practice sessions a total of 34 runs were performed (FW =

14 and RYF = 20) and 1031 impacts observed. Of the total number of impacts 175 (17 %) occurred at FW and 856 (83 %) occurred at RYF. The median number of impacts were 11.5 for FW, 50 for RYF and 18 over the two sessions combined. Table 1 summaries the accelerometry findings for each course and overall. Significant differences were revealed between courses for the mean number of impacts ($t_{(22.96)}$ = -4.70; $p < 0.001$; 95 % CI = 17.00 to 43.64), maximum peak rotational acceleration ($t_{(32)}$ = -2.636; $p = 0.01$; 95 % CI = 680.31 to 5308.38), mean acceleration duration ($t_{(32)}$ = -4.05; $p < 0.001$; 95 % CI = 0.91 to 2.76) and maximum acceleration duration ($t_{(29.51)}$ = -4.06; $p = 0.001$; 95 % CI = 4.21 to 14.94). No other significant differences were found.

Median peak translational accelerations were 18.4 g, 17.9 g and 18.1 g for FW, RYF and overall, respectively. Frequency distributions revealed the majority of translational accelerations (65.8 %) occurred between 10 and 20 g. 2.3 % of all translational accelerations were above 80 g. The 95th percentile for translational acceleration peaks was 58 g.

Median rotational accelerations were 2017.6 rads/s^2, 2262.7 rads/s^2 and 2161.8 rads/s^2, respectively for FW, RYF and overall. Data analyses showed almost identical frequency distribution of rotational accelerations between 1000-2000 and 2000-3000 rads/s^2 (24.7 % and 24.4 %, respectively), which accounted for the majority of all accelerations. Of the 1031 rotational accelerations, 7.2 % were greater than 6000 rads/s^2. The 95th percentile for rotational accelerations was 6749.9 rads/s^2.

Results revealed the median acceleration durations for FW, RYF and overall were 3.8 ms, 5.1 ms and 4.6 ms, respectively. Whilst the greatest percentage of accelerations occurred with a duration of <3 ms (frequency 388; 37.6 %), 93.8 % of all accelerations occurred with a duration less than 15 ms. The 95th percentile for impact duration was 17 ms. Distribution of all translational and rotational accelerations along with impact durations are shown in Fig 2.

When data were compared between race categories, significant main effects were found for the number of head acceleration ($F_{3,34}$ = 9.86; p <.001; η_p^2 = .50), mean translational acceleration ($F_{3,34}$ = 3.07; p = .043; η_p^2 = .24). and peak rotational acceleration. ($F_{3,34}$ = 2.97; p = .047; η_p^2 = .23). *Post hoc* analyses revealed the significant differences occurred between Elite men and all other categories for the number of accelerations (p < .005) and between Elite men and Senior men for mean translational acceleration (p = .045) and peak rotational acceleration (p = .049). Mean results were 19.50 ± 17.38, 51.79 ± 26.64, 15.00 ± 6.29 and 9.75 ± 26.14 accelerations; 23.98 ± 9.13, 20.61 ± 3.64, 29.02 ± 8.00 and 27.80 ± 10.56 g mean translational accelerations; and 6731.79 ± 3540.29, 10410.89 ± 3439.03, 8079.01 ± 3357.11 and 6084.39 ± 646.35 rads/s^2 peak rotational accelerations, for Elite juniors, Elite men, Senior men and Master, respectively.

4. Discussion

The purpose of this study was to determine translational and rotational accelerations of the head during DHI mountain biking and to determine whether course type influences these loads. It was hypothesised that the accelerations experienced during DHI would differ by course and be greater than those previously observed during other cycling disciplines. Whilst translational accelerations during DHI were comparable to those reported for BMX[9], the number of translational and rotational accelerations were greater during DHI. Therefore, the hypothesis was only partially accepted.

Despite being nearly 3 minutes shorter in duration, the mean number of accelerations observed were significantly greater for the RYF course than for FW. This in part, may be due to differences in course design. Shorter, but more technical tracks, such as RYF, may result in greater vibrations and therefore head accelerations. Though both tracks had fast, open top sections, RYF had more corners and tighter radius corners over the length of its course. This might require greater energy expenditure due to riders performing more decelerations through braking into the corners and subsequent accelerations out of the corners to maintain velocity. This may have contributed to greater fatigue and subsequently the greater number of head accelerations reported for the RYF track despite its shorter length. These results suggest that race duration does not necessarily determine the likely number of impacts sustained, and course profile is more indicative. This idea is supported by Veicsteinas et al (1984)[25], who reported $\dot{V}O_2$ levels of elite Slalom and Giant Slalom skiers of 200 % and 160 % of $\dot{V}O_{2max}$, respectively. Given that, Slalom events are typically 15-45 s shorter than Giant Slalom events and consist of closer gate placements, these finding support the idea that shorter, more technical events can require greater energy contribution and therefore potentially be more fatiguing than longer, less technical events.

Both the mean and median number of accelerations over the two test sessions were greater than those observed per practice and match play in soccer[10]. Munce et al. (2015)[10] observed 27 practice sessions, 9 pre-match warm up sessions and 9 matches over a season and reported the median number of accelerations in soccer practice sessions was 9 per session and 12 per match. Given that, the data presented in the current study are the mean from only two timed practice runs per rider per race (riders did not want to test during the race itself), it is likely the total number of accelerations riders will experience over a course of a race season will be much higher than those reported for soccer.

The mean peak translational accelerations were not significantly different between courses and were comparable to those reported for BMX[9]. However, as with BMX, mean peak translational loads were greater than those reported for contact sports[10,11,18,26-28]. Though maximum peak translational loads were not reported for BMX[9], the present study found these to average ~80 g over the two course, with individual values being recorded up to the 160 g cut off. Whilst the majority of translational accelerations were sub-concussive (10-20 g), 2.3 % of all accelerations recorded were above the reversible threshold for brain injuries[16]. Peak translational accelerations were comparable to those reported by Scher et al[14] during snowboarding back edge catches. However, as previously stated, this and other research into skiing and snowboarding head accelerations[12,13] have all used video analysis or Hybrid III dummies to determine accelerations. Additionally, the values reported have all been from direct head impacts with the ground. In contrast, the head acceleration data in the present study were recorded under normal riding condition in the absence of crashes, with the exception of one participant. Given that, previous research[15] has shown that repeated head accelerations can compromise cognition and brain tissue integrity and that data from the present study is from only two test sessions, the results would suggest that over the course of a full race season, DHI riders may be at an increased risk of sustaining irreversible brain injuries and that direct head impacts with the ground may be even higher than those reported for snow sports.

Mean rotational accelerations were again not significantly different between courses. However, DHI values were almost double those reported for BMX when not using a protective neck brace. However, they were comparable to BMX when BMX riders wore neck braces[9]. This again, may be a result of course demands and the tighter radius corners DHI riders have to negotiate compared to BMX. This may have lead riders in the present study to rotate their heads more to look round the corners than would be required in BMX.

Maximum peak rotational accelerations differed significantly between FW and RYF, with higher reported values for the latter, again, this is likely the result of differences in course design. Maximum peak rotational accelerations averaged 8566 rads/s^2 across the two sessions, with the median being approximately 2000 rads/s^2. Just over 7 % of all recorded values were again greater than the proposed threshold of 6000 rads/s^2 for reversible brain injuries[16]. In addition, every rider reported at least one impact over 12,000 rads/s^2. Of note, one rider reported crashing during one of his runs and sustained a head impact with the ground resulting in translational and rotational accelerations of 160 g and 18,000 rads/s^2 respectively. However, it should be noted, that the true magnitude of the translational acceleration might have been much higher, as the sensors had an upper threshold of 160 g. If these values are typical of forces during DHI crashes and from riding DHI without crashing, then the present study highlights the increased risk of sustaining potentially serious brain injuries during DHI riding when compared to other sports such as skiing and soccer[10,11,14].

Acceleration duration is also an important factor in the development of concussions and mTBI's[17]. Duration threshold for brain injury have been reported to range between 10 and 15 ms[16,17]. Though the present study found that most accelerations occurred with a duration of less than 3 ms, almost 94 % of all recorded accelerations occurred with a duration less than 15 ms, whilst the mean acceleration duration over the two courses was 5.7 ms. Both mean and maximum acceleration durations were significantly greater for RYF, again possibly indicating the influence of course technicality on these metrics. Based on previous research[16,17], these results again points to an increased risk of sustaining brain injuries in DHI participants.

Despite the proposed increased risks of serious head injury in DHI, the association between 'likely' concussive impacts and failure to manifest in a concussion has been reported elsewhere and supports the proposition that the symptomatology of concussion does not always correlate with biomechanical data[19]. An understanding as to why an individual is more or less likely to receive a concussive blow remains controversial. Individual tolerance to such impacts cannot be discounted also. Additionally, despite the high peak values reported in the present study, the majority of translational and rotational accelerations for both courses were of a sub-concussive magnitude, yet it is not currently known to what extent these lower magnitude accelerations may contribute to brain health and function and whether they have the potential to lead to degenerative conditions such as chronic traumatic encephalopathy (CTE). Of great interest to future researchers would be the perception of athletes and coaches in self-reporting symptoms of concussion, prior to formal head injury assessments being undertaken.

Data compared between race categories provided some insight into which groups may be at greater risk of sustaining head injuries. Elite men experience significantly more head accelerations over 10 g followed by Elite juniors than the other two groups. However, it was also noted that the mean translational loads over the two tracks were lower for Elite men and juniors than for Senior and Masters men. Whilst the higher number of head accelerations for the two Elite groups were possibly due to higher race velocities, the mean translational loads may have been lower as a result of possibly greater neck strength and conditioning. Previous research has suggested that athletes with smaller and weaker necks are more likely to experience greater displacements of the head following impulsive neck loads[29]. This is further supported by data from youth BMX riders, which found that those in the eldest of the youth groups were generally had greater neck musculature, resulting in reduced neck loads[30]. This might be the case for Senior and Masters rider, who potentially spend less time on muscular conditioning. However, further research is need to confirm this supposition.

5. Conclusions

In conclusion, this study found higher translational and rotational head accelerations during DHI than previously reported for other cycling disciplines, snow sports and contact sports and that course design rather than race duration are possibly better predictors of the number and magnitude of accelerations sustained. Additionally, the study also revealed that riders are potentially at risk of sustaining mTBI's and irreversible brain injuries when data are measured against previously reported thresholds and that less experienced riders are likely to be at a greater risk. However, further research is warranted to determine exactly how much brain function may be affected because of DHI induced head accelerations. The findings of this study also indicate the need for long-term athlete monitoring to establish the risks associated with both concussive and sub-concussive accelerations. Whilst GPS technology was not used in the present study, future research might seek to utilise such technology in order to synchronise head accelerations to specific point on a course to enable better understanding of the types of terrain and obstacles that result in the greatest risks.

Practical implications

- Results highlight the potential risks of sustaining mTBI's because of participation in DHI.
- Coaches and riders should be aware of the influence different courses may have on the number and magnitude of head accelerations.

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Figure 1. Xpatch Accelerometer sensor placement.

Figure 2. Frequency distribution of all translational and rotational accelerations and impact durations for both courses.

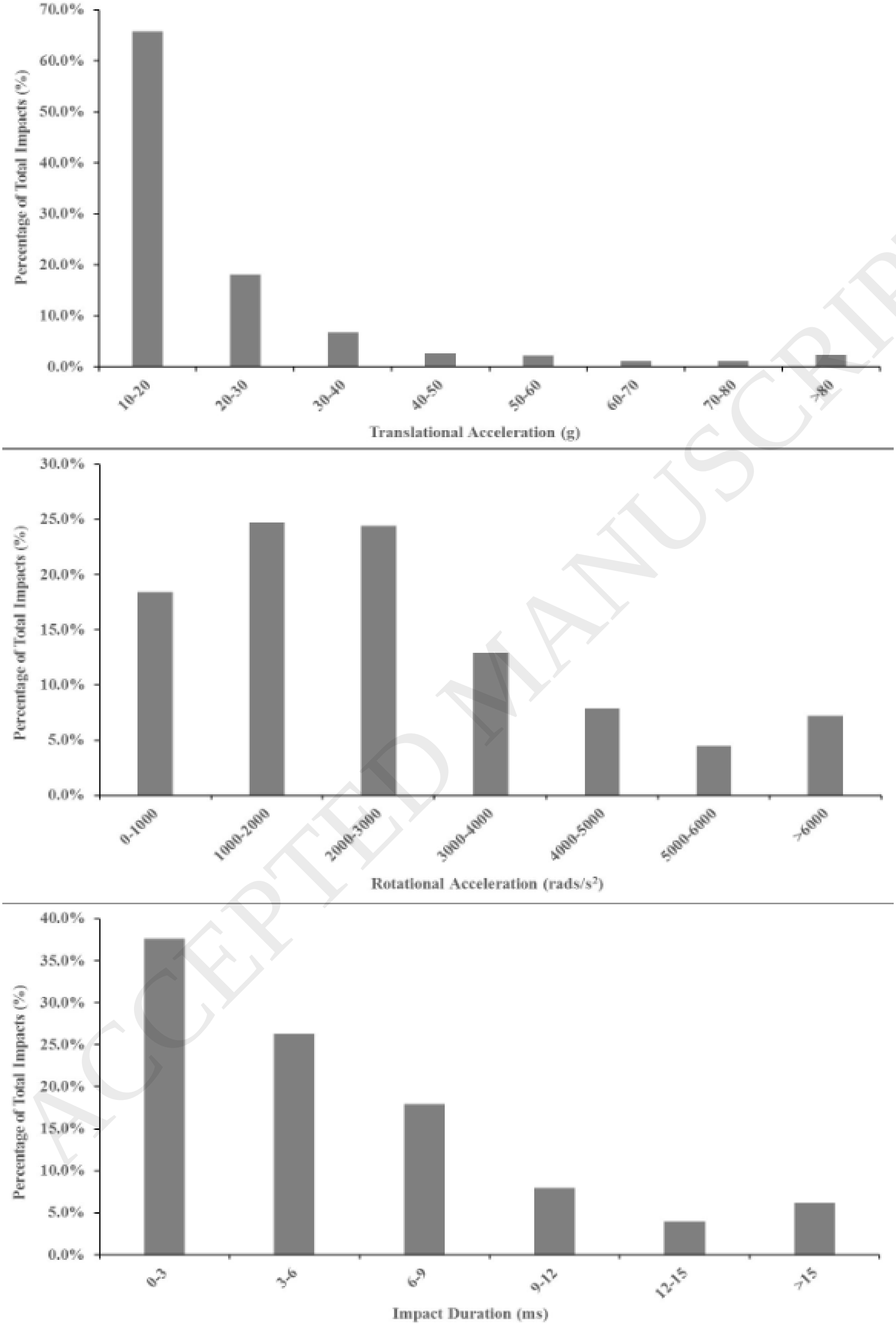

Table 1.

	Course			
	FW	**RYF**	**p value**	**Overall Mean**
Mean Number of Impacts	12.5 ± 7.6 (8.1-16.9)	42.8 ± 27.4 (30.0-55.6)	<.001	30.3 ± 26.1 (21.2-39.4)
Mean Peak Translational acceleration (g)	25.1 ± 7.8 (20.6-29.6)	24.1 ± 7.8 (20.5-27.8)	.72	24.5 ± 7.7 (21.8-27.2)
Maximum Peak Translational acceleration (g)	72.5 ± 33.3 (53.3-91.7)	85.2 ± 34.9 (68.8-101.5)	.30	79.9 ± 34.3 (68.0-91.9)
Mean Peak Rotational acceleration (rads/s^2)	2453.0 ± 918.6 (1922.6-2983.4)	2738.8 ± 639.3 (2439.6-3038.0)	.29	2621.1 ± 766.9 (2353.5-2888.7)
Maximum Peak Rotational acceleration (rads/s^2)	6805.4 ± 3073.8 (5030.7-8580.1)	9799.9 ± 3381.7 (8217.1-11382.4)	.01	8566.8 ± 3541.7 (7331.0-9802.6)
Mean Impact Duration (ms)	4.7 ± 1.2 (4.0-5.3)	6.5 ± 1.4 (5.8-7.1)	<.001	5.7 ± 1.6 (5.2-6.3)
Maximum Impact Duration (ms)	11.6 ± 4.5 (9.0-14.2)	21.2 ± 9.1 (16.9-25.4)	.001	17.2 ± 8.8 (14.1-20.3)