

Impact and Injury Response of Long Track Speed Skaters

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ABSTRACT

The following study presents a combined numerical-experimental investigation into the impact and injury response of long track speed skaters when impacting the protective boarding around the track. The high speeds common within the sport combined with the inherent slipperiness of the ice create a high probability for falls. When falling, racers inevitably impact the safety boarding surrounding the track with a high velocity. Despite the safety measures taken, severe injuries are still occurring.

The methods used within this study include an accident analysis study, experimental boarding impact and friction testing, and numerical simulation of both the experimental boarding impacts and recreated human skater impact cases. The method is applied to a modern boarding design, showing skater impact injury sensitivity to impact velocity and angle. Further skater injury response increases were observed when boarding pressure, friction and attachment height were varied. The approach developed here is considered applicable for other boarding designs and a useful approach/tool for establishing safety response requirements as it allows for objective comparison between boardings of a completely different design.

INTRODUCTION

PROBLEM DEFINITION

During long track speed skating, skaters travel around a 400 meter oval track over distances ranging between 500 and 10,000 meters achieving speeds up to 60 kilometres per hour. Such speed combined with the slipperiness of the ice creates a high injury risk during falls, especially in the corners.

In order to reduce the potential for injury, the International Skating Union (ISU) has established safety measures implemented for the race surroundings. Protective boarding are required in the curves measuring at least 80cm high and at least 15cm thick, extending at least 12m into the straights [1]. The mats are covered

with a water and cut-resistant material and must be fixed in place in such a way to avoid serious injury in case of a collision between a skater and the protection.

Despite these safety measures severe injuries are still occurring. An important reason is the lack of biomechanical background supporting such standards. Over the past 50 years the study of numerical human body modelling has allowed researchers to investigate the biomechanics involved in impact and injury scenarios. Such work has been primarily motivated by the automotive industry in an effort to reduce occupant injuries. Numerical modeling has been a tool used to achieve these goals where validated human body models are subjected to a wide range of impact conditions, helping to indicate what safety designs result in the reduction of injury severity thereby benefiting occupant safety [2-7].

As the use of such models continues to increase, so has the confidence in their accuracy and subsequent applicability in non-automotive scenarios [8]. Sport impact scenarios in particular present several similarities where the impact severity expected of the participant is of a similar magnitude to automotive impacts.

AIM AND APPROACH OF THE STUDY

This study is focused on understanding the biomechanics of the impacts and injuries sustained by professional long track speed skaters using a combined numerical-experimental approach. The approach can be defined in the following three steps:

1. An accident and injury investigation examining up-to-date literature, surveying experts involved in the sport and analyzing actual impacts recorded during professional long-track speed skating events.
2. An experimental study, performing pendulum impact tests on a commercially available air-filled boarding to investigate the impact response and provide validation data.
3. A skater-to-boardings impact numerical study varying skater posture, velocity and angle, as well as boarding

attachment method, internal pressure and skater-to-boarding friction coefficient.

The approach developed fulfills the second aim of this study which is to accommodate the objective evaluation of boardings of completely different designs.

METHODOLOGY

ACCIDENT AND INJURY INVESTIGATION

Information on injury scenarios, injuries and the influence of the impact protective boarding was obtained to understand and characterize the events and injuries occurring in professional skating accidents. Information was obtained from the following three sources:

1. Literature review including published articles, internet searches, sports injury archives and consumer safety information
2. Interviews of coaches and medical staff of Dutch commercial long track skate teams. Participants were asked to fill in a questionnaire, followed up by an interview to discuss in detail the answers to the questions.
3. Analysis of video recordings of seven professional level long-track skating accidents (with and without injury). The following information was gathered: accident location, direction, the conditions before (gliding phase), during and after impact with the boarding.

EXPERIMENTAL INVESTIGATION

The experimental investigation was performed to satisfy two project objectives: (1) gather experimental performance responses that represent impact characteristics similar to those seen in skate accidents and (2) investigate parameter variations of an existing boarding design as accepted by the ISA safety regulations. Two experimental methods were employed to obtain the appropriate impact response data. The first was pendulum impact testing against an actual boarding system and the second was friction testing of the materials surrounding the boarding material, with which skaters engage in contact during impact.

The impact safety system considered within this study was an air-filled skater protection system developed by Sidijk BV in the Netherlands. In professional speed skating events, 18m long radial sections of boarding are used to provide protection to skaters in the corner regions. Each section has a height of 1.2m and a depth of 0.6m. The boarding is divided into 8 chambers, openly connected to one another through 0.1m diameter holes placed every 0.5m on the walls that join adjacent chambers as can be seen in Figure 1. Each section is inflated through a single fan which can generate internal pressures between 1400 and 4500 Pa.

The system is connected to the ground through steel rods that thread through both a flap connected to the

underside of the boarding and eyelets connected to the ground every 0.5m. Figure 2 outlines the flap, steel rod and eyelets used in the connection.

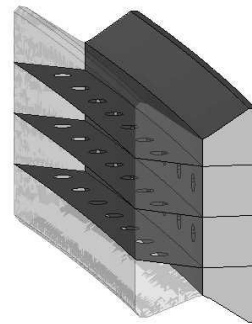


Figure 1 – CAD drawing of boarding; 8 open chamber construction method

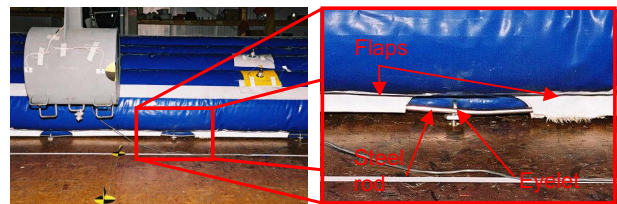


Figure 2 – Boarding-ground attachment method

For all professional events a single layer of cutting resistant Kevlar® Icetax® material is placed over top of the boarding system. This is to prevent skaters from penetrating the boarding with their skates, thereby reducing the risk of cutting injuries. It is noted here that the cover, being made of Kevlar®, presents significantly stiffer material properties as compared to the boarding material itself.

Pendulum Impact Experiments

Within this study it was assumed that the most severe impact event was that which directed the greatest amount of skater impact energy normal to the boarding face (55 km/hr at 40°-tangential). This condition was found in the accident investigation study and was therefore used as the basis for the pendulum test setup. Ideally, a free moving, angled impact mass equal to the average skater would have been desired to conduct these tests. However, such a setup was considered to be too complicated. Instead, a rotating perpendicular pendulum impact test condition was chosen with the setup as seen in Figure 3.

The pendulum was comprised of a 4.09 m long square steel tubing (23 kg), having a 0.405 m diameter by 0.45 m wide steel drum (55kg) connected to its impact end. In total the device had a mass of 78 kg, which approximated the 50th percentile male. The shape and size however were not considered in this representation. The device was designed to generate the perpendicular impact conditions of a skater at an impact height of 47

cm off the ground. Pendulum motion was achieved through a single rotational joint connected to the ceiling of the test hall. The pendulum was accelerated to its impact velocity through the influence of gravity, where the maximum possible release height was used to generate an impact velocity of 9.8 m/s. This was equal to the perpendicular component of a skater with the impact conditions described above. Such an impact was thought to represent a worst case scenario, where all of the skater's energy is oriented perpendicular to the boarding system. This of course would not happen in real-life as a portion of an impacting skater's energy is directed laterally along the length of the boarding. Further, it is noted here that the radial nature of the pendulum motion induced a vertical impact response on the boarding throughout impact. This however was thought to be of minimal influence due to the large radial arm of the pendulum.

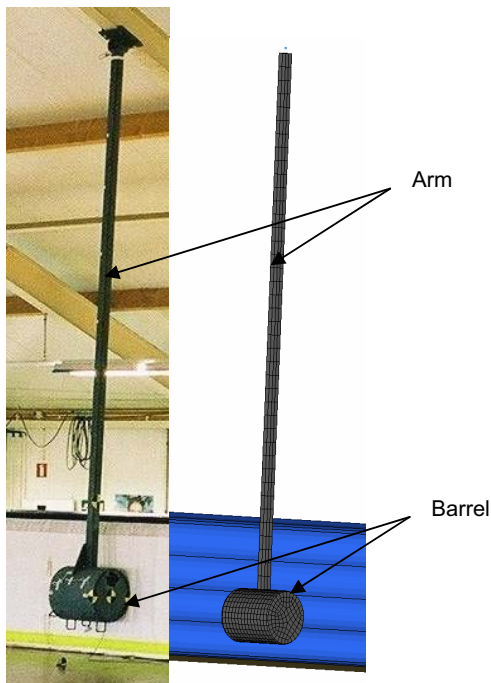


Figure 3 – Experimental (left) and simulated (right) pendulum impact device

All tests were performed on an 18 m straight section of boarding. A straight section was chosen to determine the impact properties of the boarding system for a relatively simple and well-defined set-up. These properties are implemented in the numerical model that determines human injuries during boarding impact in a curved section.

Acceleration was measured during the impact through 1-axis accelerometers located on the back face of the pendulum barrel, measuring the tangential acceleration of the pendulum. High-speed video was used to record the impact with a frequency of 1000 Hz. The barrel velocity and displacement (i.e. penetration into the boarding) as a function of time were calculated by integrating the acceleration signal. The horizontal

displacement component was extracted from the radial motion of the pendulum and used as the penetration of the pendulum into the boarding. The initial velocity required for these calculations were obtained using simple kinematic equations and through analysis of the high-speed video. Both methods showed the same impact velocities. The acceleration signals were filtered using a CFC 180 filter, removing significant noise in the system.

As this was an air filled system, internal boarding pressure was measured before and during the tests. The static pressure of the system was measured immediately prior to the impact while the dynamic pressure of the system was measured in two locations during the impact. The first was located 1m lateral of the point of pendulum impact and the second was located 7 m lateral from the point of pendulum impact. The objective was to investigate any time dependent pressure differences along the length of the boarding system.

A total of twelve tests were performed to investigate the only two parameters that could be changed during realistic implementation of the boarding system: (1) initial internal pressure and (2) the addition of the Icetax[®] boarding cover. Table 1 summarizes all tests performed. Two repeat tests at an internal relative pressure of 3000 Pa were performed to examine experimental repeatability. The same repeatability tests were done for the Icetax[®] condition and constituted all tests performed with the cover. It is noted here that a pressure of 1900Pa is requested by professional skaters during events as they feel the pressures used in amateur events (3000Pa) provides too much rebound when coming away from the boarding.

Table 1 – Pendulum impact test matrix

Test Number	Test Scenario	Relative Pressure (Pa)
F063110/1/2	Without cover	3000
F063113	Without cover	1900
F063114	Without cover	1400
F063115	Without cover	2500
F063116	Without cover	3500
F063117	Without cover	4400
F063121	Without cover	3950
F063118	Icetax [®]	3000
F063119	Icetax [®]	3000
F063120	Icetax [®]	3000

Friction Experiments

Tribological experiments were conducted to measure the coefficient of friction (COF) between skate suits and boarding materials. The experiments were performed on the TNO slider-on-sheet tribometer (Heide et al. 2001), with a normal force of 250 N or 100 N and a sliding velocity of 0.50 m/s. While this velocity was noted to be lower than those observed during impact of the skater and boarding during a real accident, it was required to ensure measurement accuracy within the experimental limits of the device. The temperature during all

experiments was 21 °C and the relative humidity was 43%.

A part of an actual skating suit was moved over the surface of a skate boarding material. This suit part was mounted on top of a skin material of commercially available crash test dummies. The dummy skin was thought to be appropriate for approximating the stiffness properties of human skin behind the suit. Two skate suits and two boarding materials were made available for this testing by both the KNSB and Sidijk. Professional and amateur skate suits were used along with a commercial advertising cover and the Icetax[®] cut resistant material. The surfaces of the boarding materials were cleaned with ethanol to create similar conditions for all experiments.

The advertising cover itself was further observed to possess two different types of print surfaces. These included the base print surface and the advertising print material placed overtop. Prior to testing these two surfaces were observed to have a matte and glossy feel; therefore, separate tests were performed on both of these regions.

NUMERICAL INVESTIGATION

The numerical work first required the development of a numerical boarding model, with response characteristics evaluated against the experimental pendulum impacts. Following validation, an existing MADYMO human body model (de Lange et al., 2005) was then used for investigating the kinematics and injuries observed throughout impact. A number of variation studies were performed evaluating skater impact characteristics (position, angle and velocity) and boarding design parameters (internal pressure, friction and attachment methods).

Boarding Modeling

For the purposes of this study, two boarding models were created to achieve the goal of accurately modeling the human impact response. The first model represented the 18m long straight section that was used in the experimental testing. The second model represented an 18m long curved section having a midline radius of 32m as used at current ice skating tracks.

Both models were generated using CAD drawings provided by Sidijk, with the individual chambers connected adjacently to one another through the 0.1 m diameter holes. The surfaces were modeled using triangular shell elements with an average element edge length of 10 mm. The element size was chosen such that the model could replicate the deformation expected during inflation and skater impact. Material properties representing Bisonyl were implemented in a linear elastic isotropic material with a density of 1400 kg/m³, a Young's modulus of 800 MPa and a Poisson's ratio of 0.3.

The model was generated in its undeformed state and therefore required a pre-simulation with incoming airflow to generate an internal pressure and deformed boarding shape. The pre-simulation was run for 0.2 sec to provide a stabilized condition. The desired pressure was defined by a volume flow rate, which was activated for the first 0.1 seconds of the pre-simulation. The undeformed and deformed boarding shape can be seen in Figure 4.

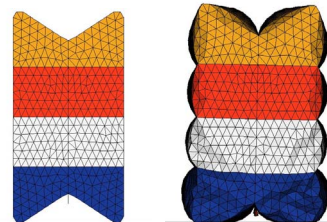


Figure 4 – Boarding system pre (left) and post-inflation (right)

The boarding attachment was simulated by rigidly restraining individual nodes every 500mm on the attachment flap modeled underneath the boarding. This replicated the attachment of the steel rod to the floor in the real condition. Additionally, during the pre-simulation, the attachment nodes were displaced along a defined path to pull the boarding down to the appropriate height. This was observed to increase the resultant internal pressure of the system and was considered as a parameter during the variation study.

Simulation of the pendulum was implemented through the use of a rigid finite element model. Detailed geometric representations of both the barrel and arm were created to capture the separate interactions of these components with the boarding throughout impact. The barrel was given an initial velocity equal to the values measured from the high-speed video. Contact was defined using a penalty based method where the material properties of the boarding were used to define stiffness. A coefficient of friction of 0.30 was used.

Skater Impact Simulation and Variation

Simulation of the impacting skater was implemented using the MADYMO 50th percentile male facet human body model [9] with detailed facet leg model [10]. This model provided sufficient injury response data, while maintaining a relatively low computation time.

The influence of skater impact parameters were investigated by varying skater position, impact angle and impact velocity. Figure 5 shows two skater positions considered for this study, both of which were obtained from actual impacts. Preliminary simulation work indicated that these two positions, defined here as *lying-side* and the *lying-back*, were the best and worst case scenarios respectively from an injury severity standpoint. These scenarios were simulated for velocities of 40, 50 and 60 km/hr, and impact angles of 20°, 30° and 40° tangential from the boarding. For all simulations the boarding parameters were set to represent ideal conditions used in professional events and included a

relative internal pressure of 1900Pa, an attachment height of 30 mm and a coefficient of friction of 0.30.

The influence of boarding design parameters were investigated by varying boarding internal pressure, flap attachment height and boarding-to-skater coefficient of friction. For these simulations, both the *lying-side* and *lying-back* scenarios at 60 km/hr and 40° were considered. Table 2 summarizes the simulation setups for this investigation.

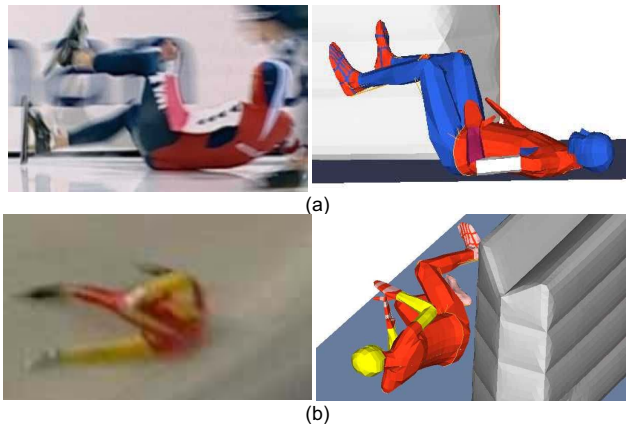


Figure 5 – Actual impact scenario (left) and simulated impact scenario (right); (a) *lying-back*, impacting feet first, (b) *lying-side*, lying and impacting back first

For these impact simulations, head and torso injury responses were considered (HIC, head 3ms acceleration and T12 3ms acceleration). These three responses were thought to be appropriate for evaluating the most severely injured body region (head) as indicated by the accident investigation and for providing whole body accelerations (T12) to indicate the global severity impact. The response of the neck, shoulders and limbs, while important, were found to be scenario specific and lacked the ability to indicate general trends observed in the variation simulations.

Table 2 – Skater impact simulation matrix

Sim	Pressure (Pa)	Attachment Height (mm)	Coefficient of Friction
1	1400	30	0.30
2	1900 (pro)	30	0.30
3	3000 (amateur)	30	0.30
4	4500	30	0.30
5	1900	5	0.30
6	1900	30 (actual)	0.30
7	1900	55	0.30
8	1900	30	0.30 (min)
9	1900	30	0.50
10	1900	30	0.70
11	1900	30	0.90 (max)

In plotting the boarding variation results, injury tolerance criteria (where a serious injury is expected) were included as a reference to the severity of the impact. For the HIC and 3 msec acceleration of the head and T12, Table 3 summarizes the injury criteria limits.

Table 3 – Injury criteria and serious injury limits

Injury Criteria	Injury limit, (> AIS3)	Source
HIC	650	Prasad and Mertz [11]
Head 3 msec	60G	Eiband (1959) [12]
T12 3 msec	60G	Crawford (2003) [13]

RESULTS

ACCIDENT AND INJURY INVESTIGATION

Literature

Skate Accidents

The injury information system of the Dutch Consumer Safety Institute [14] has data on injuries that occur during long-track skating in the Netherlands, primarily for recreational skating without discrimination for population or injury type. While such information does not apply directly to the conditions intended for this study (i.e. long-track professional skating) and represents a very broad range of data, it can provide a general idea of the injuries sustained during the sport. In total, the number of sport injuries treated at first aid facilities for recreational skaters varies between 2000 and 9700 a year for recreational skaters. In the year 1998-1999 long-track speed skating accidents were responsible for 5700 first-aid treatments. During that time, long-track speed skating was ranked third, requiring the most number of first-aid treatments for each 100,000 hours of sport (31 treatments). This is believed to be quite large as the mean number of treatments for each 100,000 hours for all sport is approximately 10.

In 2005 the Netherlands Olympic Committee and the Netherlands Sports Federation (NOC*NSF) [15] conducted a study to examine skating injuries, considering again only recreational skating. In the time period between 1999 and 2002 the study indicated an annual average frequency of treated injuries of 3500. The average estimated cost of each treatment was estimated at 770 Euros, generating a total annual cost of approximately 2.7 million Euros. Additionally, the number of treated males (51%, 1800) was similar to that of the number of treated females (49%, 1700). Almost a quarter of the accidents (23%, 800) happened with 10 to 14 year-old children and nine out of ten accidents were caused by falling. The limitation of this study however was the lack of differentiation between the type of skating sport (long track, short track, figure skating and ice hockey) considered.

Injury Type

According to the Dutch Consumer Safety Institute [14], the following locations were identified as the most frequent areas of injury during skate accidents: arm injuries (56%), head injury (20%), wrist injury (19%) and leg injuries (20%). It is noted that the percentages account for more than 100% of the data source, however victims with multiple injuries occurred. Once again, this