



**University of Dundee**

## **Establishing state of motion through two-dimensional foot and shoe print analysis**

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5 A pilot biomechanical assessment of curling deliveries: Is toe  
6 sliding more likely to cause knee injury than flatfoot sliding?  
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12 MacDonald, Rami J Abboud  
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## ABSTRACT

*Background:* The aim of this study was to determine whether toe sliding is more likely to cause knee injuries than flatfoot sliding in curling.

*Methods:* Twelve curlers participated in the study, each delivering 12 stones. Six stones per volunteer were delivered using a flatfoot slide and 6 were delivered using a toe slide. The Pedar-X® inshoe pressure system recorded the plantar pressure present during each of the slides, while a sagittal plane digital video recorded the body position of the curler. Measurements were taken from the video recordings using a software overlay program (MB Ruler®), and this combined with the Pedar-X® data gave the overall joint force in the tuck knee.

*Results:* ~~Results showed a statistically significant difference between the~~The knee joint force ~~calculated for flatfoot sliding and toe sliding, with toe sliding being~~ was more than double that of flatfoot sliding ( $p < 0.05$ ). ~~A~~ There was a strong correlation ~~was found~~ between the increase in knee joint force and the increase in the moment arm of the ground reaction force. Images produced using the 3D Vicon® system confirm that toe sliding produces a larger moment arm than flatfoot sliding.

*Conclusion:* ~~The knee is on average the most common joint affected in curlers.~~ Injuries are more likely to occur in toe sliding, compared to flatfoot sliding, due to the increase in force and moment, pushing the weight of the curler forward over the knee, which could make causing the adopted position ~~to be~~ less stable. ~~This study recommends that curlers~~ Curlers should might consider avoiding ing toe sliding ~~in order~~ to reduce the risk of knee injuries if the two types of delivery could be performed equally well.

### Key Words

Curling, biomechanics, knee injuries, toe sliding, flatfoot sliding

## INTRODUCTION

The aim of this study was to analyse the joint forces about the tuck knee during curling, in flatfoot and toe slide stone deliveries (Figures 1A & 1B), and to assess whether one is more likely to subject the curler to ~~higher musculoskeletal~~ injury than the other.

Curling is a sport played on ice between two teams of four players. To deliver a stone, players gain momentum by pulling the stone back whilst lifting their hips, followed by a drive forward from the foot on the hack (a foothold on the ice). The delivery position, involving significant hip and knee flexion, is sustained for a short period after the curler releases their stone, creating potential for injury to the player.

~~Despite this, very little research has been carried out in the field of curling. As far as the authors are aware, o~~ Only three papers have been published regarding the epidemiology of curling-related injuries. ~~Injury patterns have been assessed, but no investigations into the causative factors contributing to these injuries have been explored.~~ A retrospective study carried out in the USA analysed injury patterns amongst competitive curlers, showing that over 54% of injuries ~~were are musculoskeletal injuries~~ to the knee.[1] Berry et al.[2] surveyed participants at the 2008 World Men's Curling Championships and ~~reported found that~~ five musculoskeletal injuries, all of which were pain on curling-related movements, were sustained throughout the championships.

The third paper claimeds to find results similar to those reported by Berry et al.[2] Beere et al.[3] reported 216 injuries over a ten-year period in high-performance curlers. They declared that most injuries occurred in the back, however this turns out to be only 39 of 216 injures (18%), very closely followed by injuries to the knee at 33 of 216 (15%). Furthermore, the study failed to account for the nature of 63 injuries, the total value of injuries to the back increases from 39 to

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3 56 without any explanation and they miss-quote the findings from Reeser and Berg.[1]

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6 Altogether this questions the reliability of their study and its reported findings.

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9 Yoo et al.[4] used kinematics to investigate the differences in the delivery between elite and sub-  
10 elite curlers. Using body markers, Pedar® in-shoe system and video cameras, they analysed the  
11 centre of mass, plantar pressure and joint angles of players amongst other variables. Their results  
12  
13 centre of mass, plantar pressure and joint angles of players amongst other variables. Their results  
14 showed that elite players have a greater ability to control their centre of mass and balance whilst  
15  
16 delivering a stone. However, there was no evidence to demonstrate that this has any effect on  
17  
18 injury rate.  
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24 ~~Whilst there is no conclusive evidence showing the most common injury amongst curlers, it can~~  
25 ~~be concluded that musculoskeletal injuries to the knee do occur.[1-3]~~ The cause of ~~knee~~ these  
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27 injuries is still unknown, but is likely to be due to the physically demanding aspects of the sport:  
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29 sweeping and/or stone delivery. Several papers have been published on the topic of sweeping,[5]  
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31 but only one on the biomechanics of curling stone delivery.[4] Therefore , we undertook a study  
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33 of the biomechanics of two types of curling deliveries.  
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39 Yoo et al.[4] demonstrated a successful use of kinematics on the ice, especially in relation to the  
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41 equipment used. Ramanathan et al.[6] assessed the reliability and repeatability of Pedar-X®,  
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43 validating it as an accurate method of measuring inshoe plantar pressure and contact area. These  
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45 properties of Pedar-X® and its successful use in Yoo et al.[4] guided its use in this present study.  
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50 ~~There are many areas of the sport that have not yet been researched. Beere et al.[3] stated ‘The~~  
51 ~~importance of biomechanics....in preventing injury, particularly the tuck position during delivery~~  
52 ~~of the stone should be explored in more depth.’ This area of the sport is the gap in the literature~~  
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54 ~~that was researched in this present study. Conclusions were drawn based upon the establishment~~  
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~~of significant statistical difference in the values of the joint forces between the two delivery methods. The results of this study will hopefully be informative in preventing injuries in curlers.~~

## METHODS

This research was carried out between November 2015 and April 2016. Ethical approval was granted by the University Ethics Committee (UREC). Data was collected at Dundee Ice Arena, and The Peak, Stirling Sports Village, and analysis was conducted at the Institute of Motion Analysis and Research (IMAR), University of Dundee.

### Participants

Twelve curlers volunteered to participate in the study. Nine were amateur curlers: five male and four female. The remaining three curlers were professional male curlers. Inclusion criteria for the curlers ~~were~~ that curlers must have:

1. have curled for more than five seasons
2. been currently active in the sport
3. been able to deliver stones in flatfooted and toe slide deliveries
4. had no current injuries

~~These~~ criteria ~~were~~ selected to ensure curlers with a balanced and stable curling delivery were recruited to participate in the study, to reflect as accurately as possible real match play. For this reason, curlers wore their own curling shoes and used their own brush. Participants were provided via email the relevant information and consent documents. Dundee Ice Arena and The Peak both have sheets of curling ice and stones, regulated by the World Curling Federation.[7] The ice was prepared by staff at the ice arenas to meet the curling standards before any data collection began.

## Experimental Set-up

The Pedar-X® inshoe pressure system was used to measure the plantar pressure while the curlers delivered their stones. The appropriate size of pressure insole was selected to fit inside volunteers' curling shoes. The insoles were connected via a cable to the main operating pack, which was worn on a belt around the volunteer's waist.

Before data collection began, the distance from the participant's centre of rotation of their knee to the centre of rotation of their ankle (lower leg length) was measured according to Vicon® marker placement guidelines. Height and mass of participants were also measured and recorded. This was carried out with the volunteer wearing exactly what they would wear on the ice, (including the equipment belt), and holding their curling brush as its mass also contributes to the overall mass of the sliding curler.

## Data Collection

Before data collection began curlers formally agreed to participate, understood they could withdraw from the study at any time without giving reason, and were given the opportunity to practice delivering stones whilst wearing the Pedar-X® system. Participants delivered 12 stones: six flatfoot sliding, and six when toe sliding. The stones were delivered in a randomised order to minimise bias in the results. A digital video of the volunteer was taken from the sagittal plane as each stone was delivered.

## Data Analysis

Data from six trials for each type of slide were taken from each participant, giving 12 sets of data per curler. Three trials per slide per participant were randomly selected to be further analysed.

The joint force at the tuck (left) knee was then calculated from the data. Knee joint force is a

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3 combination of quadriceps muscle force, gastrocnemius muscle force and body weight. Each  
4 value was calculated separately before being combined to give the knee joint force.  
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9 The quadriceps muscle force ( $Q_f$ ) was calculated using the moments around the knee ( $M_k$ )  
10 (Figure 2). As the knee is static, all clockwise and anti-clockwise moments must balance.  
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13 Therefore,  $Q_f$  multiplied by the patellar tendon lever arm distance ( $Pl$ ) is equal to the force  
14 recorded from the Pedar-X® software at the left foot ( $R_1$ ) multiplied by  $m$ , the distance between  
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19  $R_1$  and the centre of rotation of the knee. Thus giving the equation:

$$20$$
$$21$$
$$22 Q_f \times Pl = R_1 \times m$$
$$23$$
$$24$$

25 It was assumed that the effect of friction was negligible as the surface being played on was ice  
26 and has a very low co-efficient of friction.[8] The appropriate value for  $Pl$  was assigned to the  
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32 trial given the angle of flexion of the knee.[9]

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 $m$ , the moment arm for  $R_1$ , was calculated using a combination of Pedar-X® data and  
measurements taken from the sagittal plane video. An overlay software, MB Ruler®, was  
applied to the video to allow measurements to be made between any two points. These  
measurements were recorded in pixels then converted into meters using the known distance  
between the centres of rotation of the knee and the ankle respectively.

With a known value for  $Pl$ ,  $R_1$  &  $m$ , the equation was rearranged to give a value for  $Q_f$ :

$$Q_f = (R_1 \times m) / Pl$$

Gastrocnemius muscle force was calculated using the same principles as quadriceps muscle  
force, using the moment around the ankle.



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3 The final force taken into account was body weight. It was assumed that all body weight was  
4 being placed through the foot, and mass through the curler's brush, stone or trailing foot was  
5 negligible. Body weight being placed through the knee was therefore the mass of the volunteer,  
6 minus the mass of their distal lower limb (from the knee down), multiplied by gravity ( $9.81 \text{ ms}^{-2}$ ).  
7 The average mass of the distal lower limb is 6.18% of the total male body mass, and 6.68% of  
8 the total female body mass.[10]  
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19 Combining these three forces gave a value for the joint force at the knee. The quadriceps force  
20 acts as a pulley as it inserts at the patella tendon. This created a vector diagram (Figure 3A) with  
21 the appropriate angles being measured from the sagittal plane video recording. As the body was  
22 not accelerating, when rearranged the vector diagram created a closed polygon (Figure 3B) when  
23 the resultant vector (Rf) (the knee joint force) was added in. The size and angle of this vector can  
24 be calculated using trigonometry.  
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### 34 **Statistical Analysis**

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36 The statistical analysis was carried out using SPSS® version-22. The skewness coefficient was  
37 used to confirm that data were in normal distribution. The General Linear Model statistical  
38 analysis was used to analyse repeated measurements data and the Pearson correlation coefficient  
39 was used to analyse correlations between the data. The significance level,  $p$ , was set at less than  
40 0.05.  
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## RESULTS

Twelve curlers volunteered to participate in the study, however due to a different sliding technique of one participant, their data was removed from the study before analysis began. The remaining 11 participants were aged between 17 and 37 years old (mean: 23.36, SD 6.05), with a mean height of 1.76 meters (SD 0.08) and a mean mass of 76.37 kg (SD 11.67).

Calculated values for knee joint forces for the six trials from each participant, three flatfooted slides and three toe slides, were normalised by weight for each participant, and expressed as number of times body weight (BW). Figure 4A shows the mean of value for each trial, and the overall mean value between the three trials of the same slide. The highest individual joint force value calculated was 38.85 BW, while the lowest was 1.92 BW (mean: 12.25, SD 7.32).

General linear model statistical analysis was carried out on the full set of normalised data, comparing the values from each of the number of trials to the other five (Table 1).

$m$  was plotted against normalised joint force (Figure 4B). Pearson coefficient was calculated to be 0.94, while the  $p$  value was statistically significant at  $<0.01$ .

The angle of knee flexion of the tuck knee during stone delivery was plotted against the normalised joint force. The Pearson coefficient was calculated to be 0.82, while the  $p$  value was significant at  $<0.01$ . Likewise, the angle of knee flexion of the tuck knee during stone delivery was plotted against the moment arm length. The Pearson coefficient was calculated to be 0.88, while the  $p$  value was statistically significant at  $<0.05$ .

**Table 1.** Statistical significance between each flatfooted and toe slide trial

Trial	Mean Force	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Flatfooted Slide 1	8.58	1.04	6.28	10.89
Flatfooted Slide 2	7.56	0.99	5.35	9.77
Flatfooted Slide 3	8.25	1.04	5.94	10.56
Toe Slide 1	14.89	1.72	11.06	18.72
Toe Slide 2	17.15	2.55	11.47	22.83
Toe Slide 3	17.04	2.92	10.54	23.54
Trial Number	Comparative Trial Number		p-value	
Flatfoot Slide 1	Toe slide 1		0.002	
	Toe slide 2		0.010	
	Toe slide 3		0.019	
Flatfoot slide 2	Toe side 1		0.001	
	Toe slide 2		0.006	
	Toe slide 3		0.010	
Flatfoot slide 3	Toe slide 1		0.003	
	Toe slide 2		0.011	
	Toe slide 3		0.018	

## DISCUSSION

Speculation within the curling community suggests that toe sliding causes more knee injuries than flatfoot sliding.(Jones 2015, personal communication) Analysis of the results offers two reasons to suggest why toe sliding may cause more knee injuries than flatfoot sliding; an increased knee joint force and the increased moment arm of the ground reaction force (GRF).

## Knee Joint Force

~~It is commonly understood that i~~ increased joint forces increase the likelihood of musculoskeletal injury.[11] The ~~data findings displayed~~ in Table 1 portrays an increase in knee joint forces in toe slides (mean: 16.42, SD 7.59) compared to flatfoot slides (mean: 8.64, SD 3.60). This puts curlers who toe slide at an increased risk of knee injury compared to curlers who flatfoot slide.

This result can be seen in Table 1 where significant differences in knee joint forces ~~exist are~~ ~~visible~~ in every compared grouping; that is comparing flatfoot slides against toe slides,  $p < 0.05$  in all cases.

In addition to a difference in the values for knee joint force, the reported standard deviation for the normalised knee joint force values for toe sliding was 7.59N, more than double than that of flatfoot sliding (3.60N). By reviewing the data, the reason for this larger figure became apparent; toe sliding is a spectrum of foot positioning. When the player lifts their heel off the ice, this can range from millimeters off the ice to the curler's foot being almost perpendicular to the ice surface. The greater the angle between the sole of the curlers shoe and the ice surface, the greater the "extent" of the toe slide. Using the collected data and observing the videos taken from the volunteers delivering stones, shows that the greater the angle of the toe slide, the greater the knee joint force is.

## Moment Arm

While the increase in joint force is known to cause knee injuries, the results from this pilot study do not currently explain why there is the increase in joint force. Further investigation was required, and hence Vicon<sup>®</sup> motion capture and force plates were used at IMAR on the two slide positions, to simulate and determine the difference in the moment arm ~~of the~~ (not the moment)

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3 around the tuck knee. This process was carried out a total of nine times on two different curlers,  
4 and the average moment arm length was calculated. A 14 camera system, 120Hz Vicon<sup>®</sup> Nexus  
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6 2.2.3, was used to collect the data, with markers being placed according to the lower body  
7  
8 markers system.  
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11 Vicon<sup>®</sup> motion capture and force plates were used on the two slide positions to confirm and  
12  
13 illustrate the difference in the moment arm around the knee. Figure-5A depicts the line of action  
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15 of the GRF in a flatfooted slide, while Figure-5B depicts the line of action of the GRF in a toe  
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17 slide.  
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22 Moments around the knee were calculated from the data collected on the ice and from Vicon<sup>®</sup>.  
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24 Both show a statistically significant difference between flatfoot sliding and toe sliding, with p  
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26 values <0.01.  
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31 When the biomechanics is considered, a correlation between the toe-slide spectrum and knee  
32  
33 joint force is to be expected. Moments around any joint are calculated using the formula:  
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38 Moment = distance (moment arm) x force  
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41 As the curler increases the angle of their toe slide, the moment arm between their knee and the  
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43 application of the GRF increases. The value for R1 remains very similar but the distance between  
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45 the point of application of R1 and the knee increases, hence the moment increases. In this  
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47 situation the moment arm is the most influential variable in determining stability of the knee  
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49 joint.  
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53 From the results obtained in the present pilot study it can be clearly concluded that the moment  
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55 arm is correlated to knee joint force (Pearson coefficient of 0.94,  $p < 0.01$ ). A greater angle of toe  
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3 slide becomes significant because it creates a larger moment arm and therefore a larger joint  
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5 force.  
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9 The images generated by Vicon<sup>®</sup> system, Figure 5, illustrate the direction and magnitude of the  
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11 GRF in flatfoot sliding and toe sliding. While these two variables are very similar in both slide  
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13 techniques, the images clearly demonstrate the increase in the moment arm from flatfoot to toe  
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15 sliding.  
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19 This increase in the moment during the toe slide may put curlers at a higher risk of knee injuries  
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21 while using this sliding technique compared to flatfoot sliding. Adopting this position  
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24 necessitates the curler's centre of mass to be further forward over the knee, potentially causing  
25  
26 the curler to be less stable. The less inherent stability that the knee possesses the higher the risk  
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28 of potential knee injuries. In flatfooted sliding, the GRF is almost directly behind the knee joint.  
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31 This creates a small moment arm, and subsequently a small moment around the knee, locking the  
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33 knee and the lower limb into a much more stable position.  
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### 37 **Knee Injuries**

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39 The current literature does not explore the exact pathology of curling-related injuries. All three  
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41 published papers on the epidemiology of curling injuries refer to musculoskeletal injuries, but no  
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43 further information is given. Further research, case discussions and clinical imaging are required  
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45 to assess the types of injuries encountered before preventative measures can be suggested.  
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### 50 **Implications for the Sport**

51  
52 It is unlikely that every curler who toe slides would be willing, or be easily able, to change to a  
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54 flatfoot sliding technique. The results from this study, that toe sliding is more likely to cause  
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56 knee injuries than flatfoot sliding, should be a concern to the manufacturers of curling shoes and  
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3 to curling coaches, as well as the players themselves. Curling shoe manufacturers should  
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5 potentially consider the possible health risks of shoes that promote toe sliding and the financial  
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7 possibilities of new designs, whilst coaches should consider the promotion of flatfoot sliding to  
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9 prevent injuries to their players. Each curler needs to consider the risks and benefits of both  
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11 techniques, and make an informed decision on which style of delivery they choose to adopt.  
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### 16 **Recommendations for Future Work**

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18 ~~Very little research has been carried out on any aspect of Curling. Future research should involve~~  
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20 ~~3D motion capture cameras, force plates and electromyography as an accurate way of gaining all~~  
21  
22 ~~measurements. It would also allow curlers who slide with their foot externally rotated, or any~~  
23  
24 ~~other variations to the conventional delivery, to be able to participate in future studies, allowing~~  
25  
26 ~~for an increase in participant numbers to better represent the curling demographics. Comparisons~~  
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28 ~~should be made between the effect of draw weight stones and strike or guard weight stones, as~~  
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30 ~~well as using volunteers without a technically accurate curling slide, to assess the effect this has~~  
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32 ~~on knee joint forces.~~  
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42 What are the new findings?

- 43 • Toe sliding causes higher joint forces in the tuck
- 44 knee than flatfoot sliding
- 45 • The greater the extent of the toe slide, the greater
- 46 the knee joint force
- 47 • Increased moment arm in the toe slide makes the
- 48 curlers position less stable and so more prone to
- 49 injury
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**Figure Captions**

**Figure 1** Position of the curler during (A) flatfoot delivery and (B) toe slide delivery

**Figure 2** link segment diagram depicting the moment around the knee

**Figure 3** (A) force vectors acting on the knee (B) vectors resolved to show resultant force

**Figure 4** Joint force versus (A) slide position and (B) moment arm length

**Figure 5** Arrow showing the direction of the ground reaction force from Vicon® in (A) flatfoot sliding and (B) toe sliding

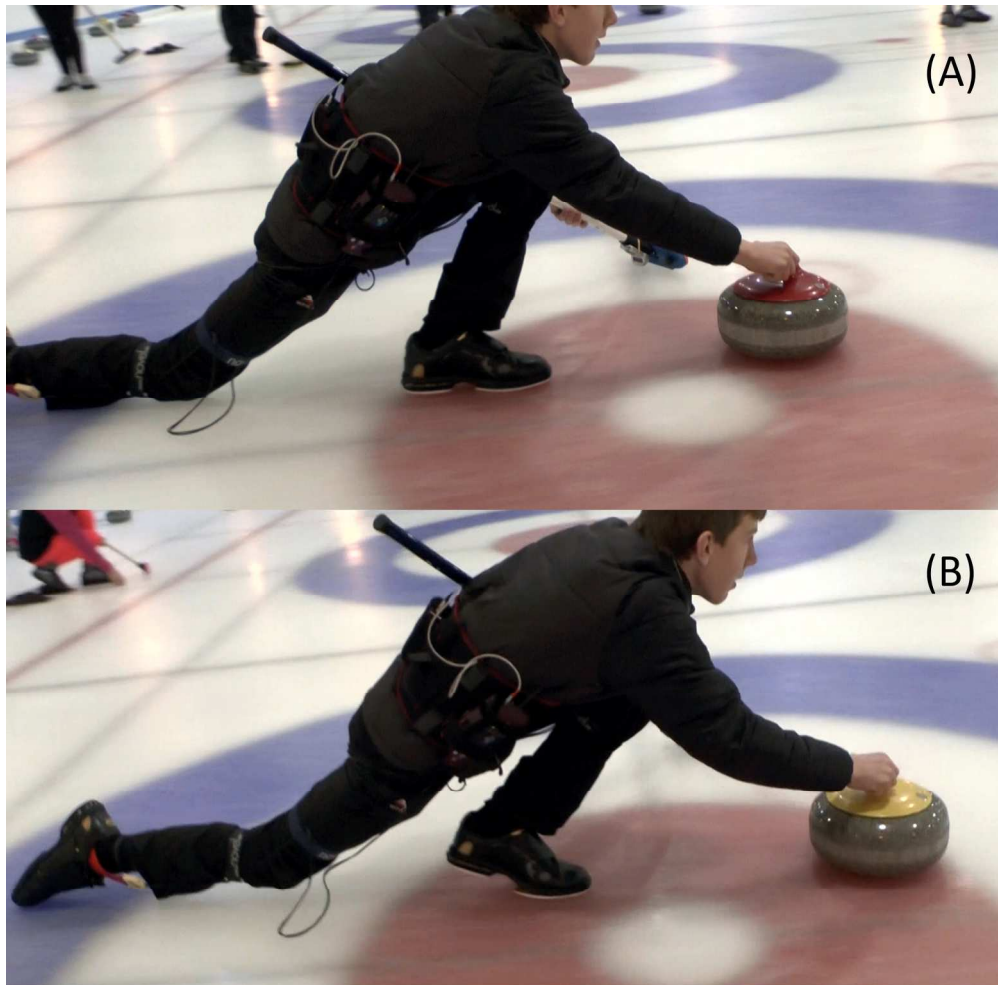


Figure 1 Position of the curler during (A) flatfoot delivery and (B) toe slide delivery

187x184mm (300 x 300 DPI)

AW Only

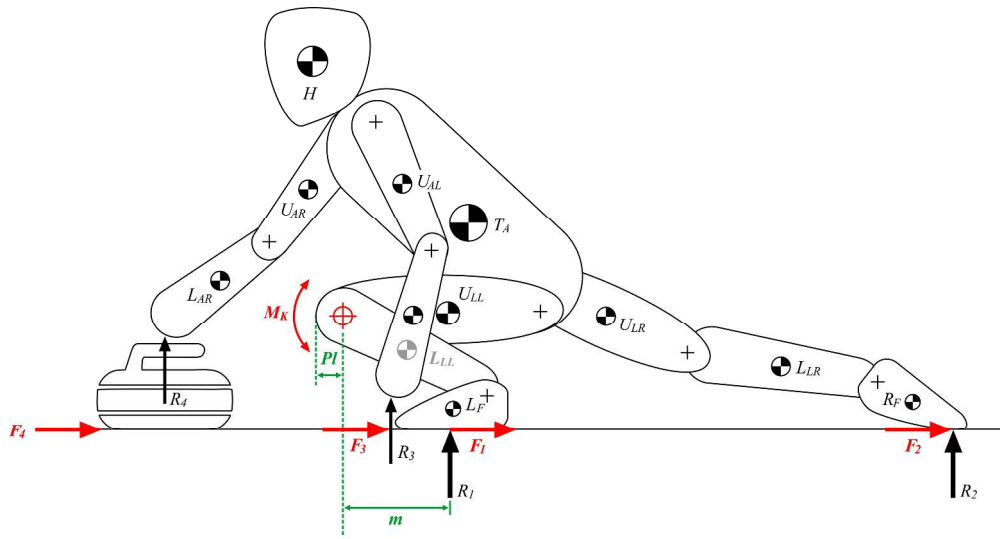


Figure 2 link segment diagram depicting the moment around the knee

319x168mm (300 x 300 DPI)

For Review Only

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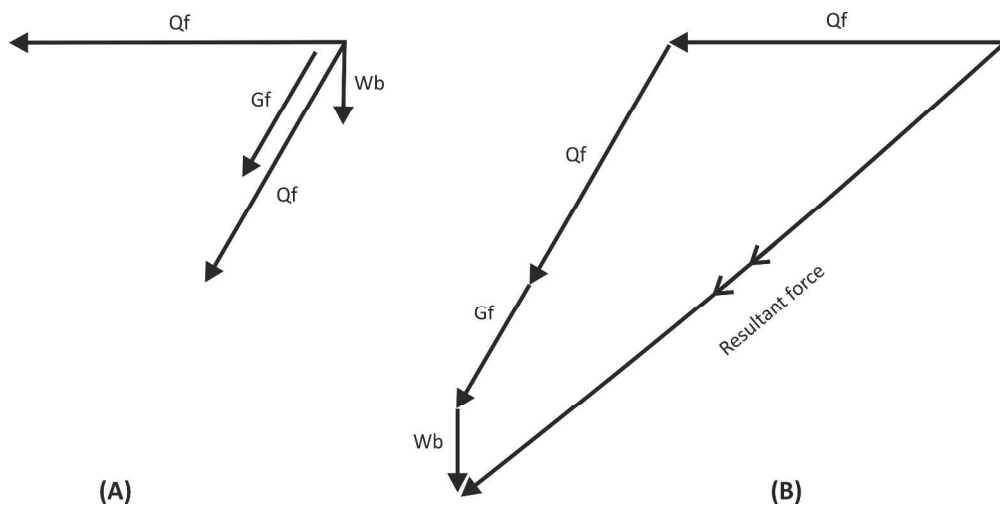
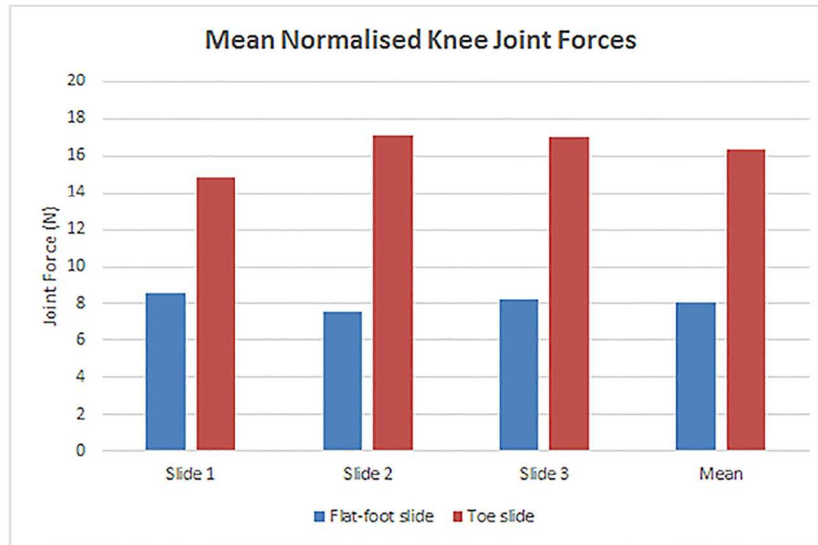


Figure 3 (A) force vectors acting on the knee (B) vectors resolved to show resultant force

264x130mm (300 x 300 DPI)

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(A)



(B)

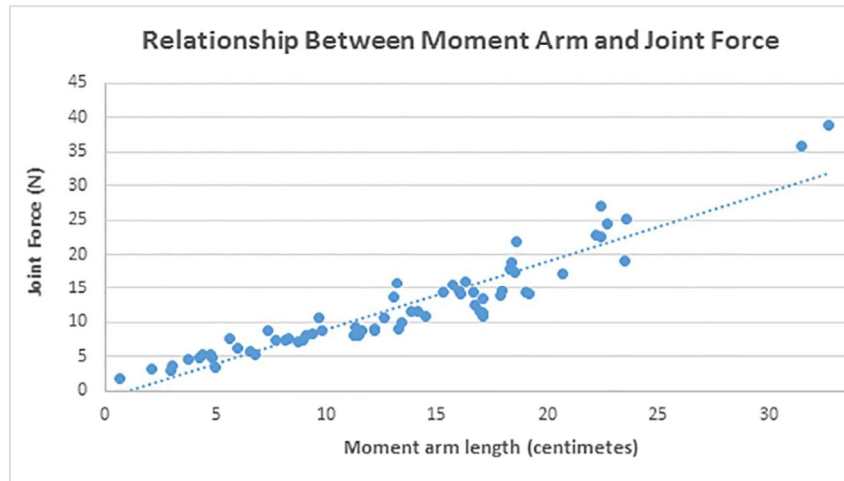


Figure 4 Joint force versus (A) slide position and (B) moment arm length

203x288mm (300 x 300 DPI)



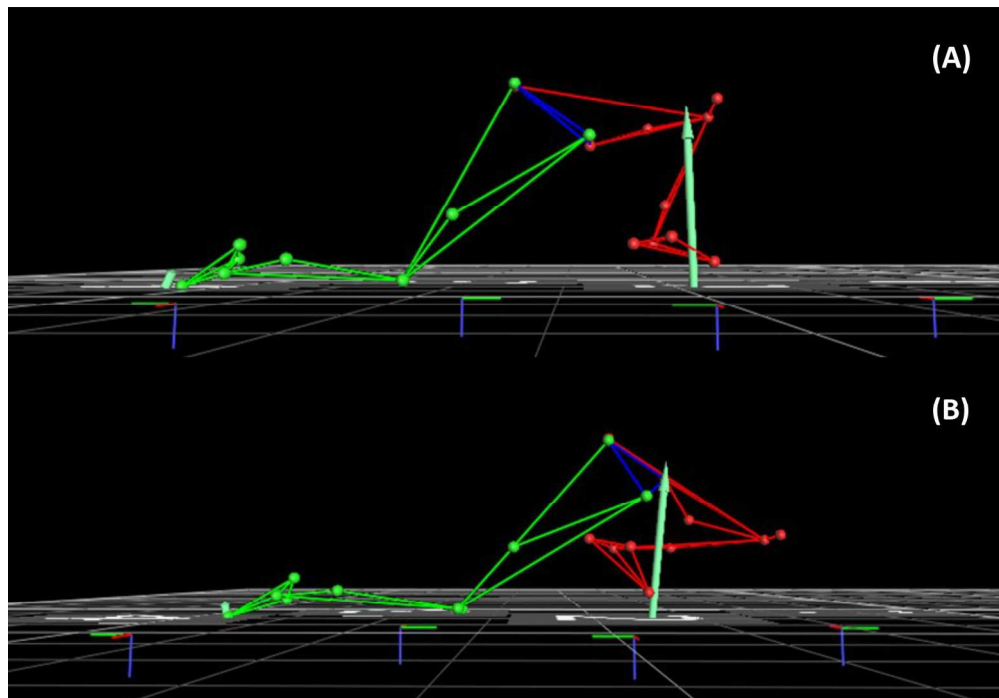


Figure 5 Arrow showing the direction of the ground reaction force from Vicon® in (A) flatfoot sliding and (B) toe sliding

175x121mm (300 x 300 DPI)

Review Only