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Does the Pattern of Muscle Activity in the Lead Lower Limb Influence Drag Flicking Performance and Injury Risk?

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Abstract

In field hockey, the penalty-corner drag flick is one of the most important offensive techniques, and a drag flicker capable of playing fast, accurate shots is an indispensable player. Regrettably, drag flickers are more injury prone than non-drag flickers, and it remains unclear why. We used surface electromyography to examine patterns of change in indices of muscle force and fatigue during the drag-flick striking phase in the lead leg rectus femoris, lateral gastrocnemius and tibialis anterior of eight elite male field hockey drag flickers (Age; *M* = 25.4 years *SD* = 2.9: Experience; *M* = 16.8 years *SD* = 7.1) and five equivalently skilled non-drag flickers (Age; *M* = 23.9 years *SD* = 2.23: Experience; *M* = 18.5 years *SD* = 3.1). Faster shots were associated with a lower index of muscle force at stick-ball contact for rectus femoris and slower rates of change in the index of muscle force across the striking phase for rectus femoris and tibialis anterior. Less accurate shots were associated with a lower index of muscle force at stick-ball contact and a slower rate of change for lateral gastrocnemius. All three muscles fatigued over 16 trials. The only difference between drag flickers and non-drag flickers was in the index of muscle force of tibialis anterior. The rate of change in the index of muscle force of tibialis anterior was slower for drag flickers compared to non-drag flickers. Patterns of change in the indices of muscle force and fatigue varied between drag flickers but did not vary between non-drag flickers. Consequently, individual differences in the lead leg muscle activation patterns during the striking phase seem more tightly coupled to shot speed and accuracy, and potentially injury risk, for drag flickers compared to non-drag flickers.

Keywords

Field data, wireless EMG, movement variability, skill specialization, fatigue, field hockey, biomechanics, drag flick, lower body, muscle activity

Introduction

In field hockey, the penalty corner is an excellent scoring opportunity because the offensive team has ten players on the field while defensive team has only five. Over the last two Olympic Games, penalty corners contributed to a third of the total goals scored (London Organising Committee of the Olympic Games and Paralympic Games Limited, 2012; Organising Committee for the Olympic and Paralympic Games in Rio in 2016, 2016). More than 50% of penalty corners were taken using the drag-flick (Organising Committee for the Olympic and Paralympic Games in Rio in 2016, 2016). Clearly, a player skilled in playing the drag flicker can exert significant influence on the outcome of a match. This is because the drag-flick affords greater variance in target, higher shot speed, and improved accuracy compared to a standard hit (Batten et al., 2016; Ng et al., 2018; Rosalie et al., 2017; Rosalie et al., 2018; Yusoff et al., 2008). However, because the drag-flick is a specialized shot which takes considerable skill to execute well, it is typically played by specialist players known as drag flickers (Rosalie et al., 2017). Despite the significant amount of training time that drag flickers dedicate to perfecting their art, or perhaps because of it, the prevalence of hip and lower back injuries amongst drag flickers is higher than non-drag flickers (Ng et al., 2016).

The importance of the drag flicker to the success of the team, combined with their vulnerability to injury, has led to growing interest in the biomechanics of drag-flicking. Studies of injury prevalence and severity (Ng et al., 2016), kinematics and kinetics in a laboratory setting (Wild et al., 2017), kinematics in a field-based setting (Rosalie et al., 2018; Yusoff et al., 2008) and the effect of individual differences (Rosalie et al., 2017) have been published. However, researchers are yet to examine the activation patterns of key muscles used in drag-flicking nor how these patterns differ between drag flickers and non-drag flickers. A thorough understanding of the pattern of muscle activation of field hockey players is essential in optimizing the design of training and rehabilitation programs that address the movement patterns and performance demands of the sport (Vanrenterghem et al., 2017). Researchers have suggested that the kinematics of the drag-flick action contribute to the higher injury prevalence amongst drag flickers; however, it might also be a consequence of the underlying pattern of muscle activity (Ng et al., 2018; Ng et al., 2016).

The scoring potential of a drag flick has been linked to two key variables. The first of these is shot speed. Shot speed is important because a faster drag flick affords the goalkeeper less time to respond to ball flight thereby increasing the drag flicker's likelihood of scoring (Eskiyecek et al., 2017; Müller & Abernethy, 2012). Drag flick speed has repeatedly been linked to the expertise of the drag flicker. Rosalie et al. (2017) reported that expert specialist drag flickers produced faster drag flicks than equivalently skilled non-specialists. Similar results were reported by de Subijana et al. (2010) and McLaughlin (1997). Moreover, Rosalie et al. (2017) reported that group related differences in drag-flick speed extended to individual differences for both specialists and non-specialists. Therefore, it is likely that the best drag flickers in the world shoot the fastest drag flicks.

Both trunk and upper limb kinematics have been associated with drag flick speed. For example, Ibrahim et al. (2017) reported that lateral and axial rotation of the trunk combined with right wrist flexion and left wrist extension were associated with stick velocity (and thus ball velocity). These findings are consistent with skilled drag flickers' whipping action and sequential acceleration of the pelvis and upper trunk (de Subijana et al., 2010). The evidence that lower limb kinematics are critical for generating ball speed is similarly compelling. A wider stance (de Subijana et al., 2010; McLaughlin, 1997) and higher lead knee extension velocity (Ladru et al., 2019) have both been associated with faster drag flicks.

Critically, previous research has shown that muscle activity of the lower limb is critical to the production of power in upper limb striking tasks (Shaffer et al., 1993). For example, Nakata, Miura, Yoshie, Kanosue, and Kudo (2013) showed that skilled baseball batters generate significantly greater peak EMG amplitudes and shorter onset latencies in several muscles in the lower limb compared to novices. Perhaps more telling is evidence that lower limb muscle activity is critical to throwing speed. This is because drag flicking involves a throw-like slinging action rather than a hitting action (Ng et al., 2018). For example, greater lower limb muscle strength, as recorded via electromyographic (EMG) amplitude of hip abductor and adductors, and higher skill level contribute to faster pitching speeds in baseball (Matsuo et al., 2001; Yamanouchi, 1998). Likewise, in sports that use a deep forward lunge at release, such as javelin, the activity of the quadriceps in the lead leg is thought critical to the generation of power through the rotation of the shoulder (Morriss & Bartlett, 1996). While this evidence supports the idea that greater lower limb muscle activity contributes to higher drag flick speed, this remains to be proven.

The second key variable of drag flick performance is accuracy. Like drag flick speed, drag flick accuracy has also been linked to the expertise of the flicker, although the evidence is less compelling. In the only study that we are aware of that compared players at both individual and group level, Rosalie et al. (2017) reported that expert specialist drag flickers were more accurate than equivalently skilled non-specialists, but only to selected targets. Moreover, group level differences in accuracy extended to differences between individual specialists, but not non-specialists (Rosalie et al., 2017). Hence, the best drag flickers are likely to be able to generate speed without sacrificing accuracy (Ladru et al., 2019; Rosalie et al., 2017).

Less is known about the kinematics of accurate drag flicks because fewer studies have been conducted on the field using representative tasks compared to laboratory-based studies. Rosalie et al. (2018) reported that a more horizontal thigh at ball release and a more vertical leg at stick-ball contact both predicted more accurate drag flicks. As previously discussed, Ladru et al. (2019) reported that a higher knee extension velocity increased drag flick speed; however, higher knee extension did not adversely affect accuracy. Critically, the role of lower limb muscle activity in drag flick accuracy is yet to be investigated. However, it is well known that lower limb muscle activity is associated with the quality of performance in sporting tasks (Girard et al., 2005). Therefore, the relationship between lower limb muscle activity and drag flick accuracy warrants investigation.

The unique kinematics that drag flickers use to produce fast and powerful drag flicks come at the cost of an increased risk of injury compared to field players who do not drag flick. Anecdotal reports of an increased prevalence of injury amongst expert specialist drag flickers lead Ng, Rosalie, Wild and colleagues to conduct a series of studies designed to first confirm whether the prevalence of injury was indeed higher amongst drag flickers compared to field players who do not drag flicker and then to identify the cause of injuries to drag flickers. The first study, a large cross-sectional study of 432 adult field hockey players including 140 drag flickers playing at local, national and international confirmed that drag flickers have a significantly higher prevalence of hip and lower back injuries compared to players who were not drag flickers (Ng et al., 2016). The author tentatively attributed this to the unique “whipping action” used when drag flicking (de Subijana et al., 2012).

To confirm this a follow-up study was completed to compare the kinematics and kinetics that drag flickers use when drag flicking compared to when hitting. This laboratory-based study revealed that drag flickers lunged further forward when drag flicking compared to when hitting resulting greater lumbar flexion, lateral flexion and rotation combined with greater hip and knee flexion and ankle dorsiflexion (Ng et al., 2018). These kinematics resulted in higher shear, compression and tensile forces in the lead lower limb and lumbar spine which the authors concluded could contribute to the increased prevalence of hip and lumbar spine injuries amongst skilled drag flickers (Ng et al., 2018).

However, Ng, Rosalie, Wild and colleagues remained unsure whether the kinematics and kinetics that they reported in Ng et al. (2018) were related to the expertise of the drag flickers, the technique the drag flickers used, or the laboratory environment. So, a field-based study was conducted to compare lead lower kinematics of drag flicking between expert specialist drag flickers and equivalently skilled players who did not usually drag flick. This study revealed that while the lower limb kinematics that drag flickers used were different to those of non-drag flickers, these kinematics did not predict shot speed (Rosalie et al., 2018). When considered alongside the higher shear, compression, and tensile forces recorded in the lead lower limb by Ng et al. (2018), this suggests that the higher forces that drag flickers experience when drag flicking are internal due to muscle activity rather than external due to ground reaction. Moreover, the correlation that Rosalie et al. (2017) reported between increasing drag flick practice and decreasing accuracy suggests that any detrimental effect of muscle forces on the quality of players' kinematics may only become apparent with higher amounts of practice. Thus, an understanding of how lower limb muscle activation patterns used when drag flicking differ between drag flickers and non-drag flickers, between individuals and across successive trials is necessary to begin to understand how muscle forces may contribute to both performance and injury risk.

Here, we report the results of a field-based experiment designed to examine the utility of wireless sEMG to analyze patterns of lower limb muscle activity that occur during the striking phase of a drag-flick. We chose to focus on the striking phase because it is during this phase that drag flickers accelerate the ball to optimize shot speed. The striking phase commences when the player first contacts the ball (stick-ball contact), includes the duration that the ball is dragged, and ends when the ball is flicked (ball release). During the striking phase the lead leg is extended reaching maximal hip flexion and knee extension at approximately front foot contact before the lead knee begins to flex reaching maximal knee flexion just prior to ball release (Ladru et al., 2019).

The aim of our study was to examine the relationship between muscle activity of the lead lower limb during the striking phase and key performance parameters including drag flick speed, drag-flick accuracy, skill specialization (drag flickers vs. non-drag flickers), individual differences, as well as the number of drag flicks taken as a surrogate measure for the amount of practice. Based on previous research, we formed four hypothesises: one, that patterns of muscle activity in the lead lower limb across the striking phase would be associated with shot speed and accuracy; two, that patterns of muscle activity would change across trials (increasing amount of practice); three, that skill specialization (drag flickers vs. non-drag flickers) would predict patterns of muscle activity; four, that only drag flickers would show individual differences in patterns of muscle activity during the striking phase of a drag-flick.

Method

This research is a secondary analysis of data originally collected by Rosalie et al. (2017). Specifically, the demographic, speed, and accuracy data reported here is based on a secondary analysis of the data collected by Rosalie et al. (2017), whereas the analysis of the electromyographic data has not been previously published.

Participants

An Institutional Human Research Ethics Committee granted approval to investigate the relationship between muscle activity in the lead lower limb and shot speed and accuracy in elite male field hockey players. Sixteen players from the Australian National Men's Field Hockey team participated in the data collection. Players were eligible to participate if they had played in at least one international match as part of the national team within the preceding 12 months and were injury-free. Players were independently classified as either a drag flicker or a non-drag flicker by two members of the coaching staff. The coaching staff classified eight of the sixteen players as drag flickers and judged all players to be otherwise equivalently skilled. The mean age of the eight drag flickers was 25.4 ± 2.9 years (min = 21, max = 29). The sEMG recording from three of the eight non-drag flickers were unusable because the EMG electrodes lost contact with the skin during data collection. The mean age of the five remaining non-drag flickers was 23.9 ± 2.2 years (min = 21, max = 28). The mean years of field hockey playing experience was 16.8 ± 7.1 years (min = 2, max = 25) for drag flickers and 18.5 ± 3.1 years (min = 12, max = 21) for non-drag flickers. Drag flickers played a mean of 106 ± 60.1 drag-flicks per week, while non-drag flickers played a mean of 4 ± 7.3 drag flicks per week. The size of each group exceeded that of two similar studies examining the performance or kinematics of elite drag flickers in which five and four elite drag flickers participated (de Subijana et al., 2012; Yusoff et al., 2008). While our sample size is smaller than recent studies of drag flicker biomechanics (e.g., Ladru et al., 2019; *n* = 19), unlike other studies all the participants in our study were competing at international level at the time of data collection.

Data Collection and Setup

Rosalie et al. (2017) collected the data on an international standard, water-based, synthetic turf field hockey pitch. A standard goal was fitted with a customized metal fascia exactly matching the dimensions of the goal face. When a hockey ball (Kookaburra Dimple Elite, Kookaburra Sports, Moorabbin, Australia) struck the fascia, it caused a dent in the surface marking where it hit. An elite coach and drag flickers selected the four areas of the goal to which drag-flicks most commonly score. These target sites were marked on the fascia. Two targets were located 0.3m below the crossbar: one 0.3m from the left goalpost (top left – TL) and one 0.3m from the right goalpost (top right – TR). The bottom two targets were located 0.46m above the playing surface because drag-flicks are not subject to the 0.3m height restriction imposed on hits. This is an important factor in the choice of the drag-flick as the preferred scoring shot. The players wore their regular training attire and used their own stick.

Experimental Design

The experiment consisted of players shooting 16 drag-flicks at the four targets in a randomized order. The players shot from a standard distance of 14.63m in front of goal, which is where a drag flicker normally shoots from during a match (Figure 1).

Figure 1. The left-hand panel shows a participant shooting a drag flick from the standard distance towards the metal fascia affixed to a standard hockey goal. The right-hand panel shows the location of the four targets on metal fascia.

We randomized the target order and counterbalanced it between players to reduce the possibility of players learning the order by watching another player complete their data collection. Players repeated any shots that missed the target after the initial 16 shots up to a limit of 25 imposed by the team's strength and conditioning coach due to training load restrictions. Players rested for 45 seconds after each shot. Given players took an average of 5 seconds to complete each shot, this equated to a work-to-rest ratio of 1:9, which has been shown to be sufficient in preventing a reduction of peak power over time (Lim & Chia, 2010).

A high-speed video camera (Casio Exilim EX-ZR800, Tokyo, Japan) recording at a rate of 120 Hz was used to capture each shot. The camera was placed on the side of the pitch 12.87 m from the sideline and 8 meters from the goal line.

At the start of each data collection, players were fitted with six wireless surface electromyography (sEMG) sensors with integrated tri-axial accelerometers (Delsys Trigno Wireless EMG, Boston, MA, USA). The electrodes were placed on the left lower limb, left shoe and stick of each player. Three of the sensors recorded muscle activity of tibialis anterior, lateral head of gastrocnemius and rectus femoris at a frequency of 2000 Hz. We chose these three muscles for three reasons. One, previous research in other sports have demonstrated that they play an important role in stabilizing stance and providing power during throwing (Matsuo et al., 2001) and hitting (Nakata et al., 2013). Two, they are related to anatomical sites where the prevalence of injury is greater amongst drag flickers. Three, in other sports these regions have been shown to provide key visual cues for anticipation (e.g., Savelsbergh et al., 2005, soccer). The EMG sensors were placed based on the SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) guidelines (Hermens et al., 2000). The sensor sites were prepared in the usual fashion for recording muscle activity using sEMG. Excess body hair was shaved. The skin was then abraded and cleaned with alcohol. The sensors were adhered to the skin using the manufacturer-supplied adhesive and taped down with rigid sports tape (Strapit Latex Free Rigid Tape, Thomastown, Australia). In addition to the muscle sensors, a sensor was placed 0.2 m from the head of the stick, where the ball contacts the stick, to record the acceleration of the stick during the contact phase from stick-ball contact to ball release. The shoe mounted sensor was placed above the heel to record foot-strike. The acceleration data from these sensors was sampled at 148 Hz. All data were recorded via a 16 channel portable data logger (Delsys Trigno TPM, Boston, MA, USA).

After the sensors were fitted, the players completed a 10-minute standardized dynamic warm-up. The warm-up was designed by the strength and conditioning staff of the team and included the following: jogging, lunges, stretching, and trials of drag-flick shots. In addition, players were familiarized with the modified goal described previously, the target locations, and the experimental protocol by playing five drag-flicks towards the experimental goal in a randomized order of targets.

Data Processing

The speed and accuracy of each shot was determined in a previous study (Rosalie et al., 2017). The high-speed video record was analyzed frame-by-frame using Proanalyst 3D Professional (Xcitex, Woburn, Massachusetts, USA) to determine the average horizontal ball speed. Two researchers independently determined the flight time of the ball by subtracting the frame number at, “ball release,” to the frame number at, “ball impact,” on the target. The known distance of 14.63 m was divided by flight time to determine shot speed. An interclass correlation was used to examine the inter-rater reliability. If a disagreement existed, researchers used the average of the two speeds for the statistical analysis of group and individual differences in shot speed. Accuracy, in terms of radial error in millimetres, was measured by two researchers using a tape to measure the distance between the ball indentation mark on the fascia and the intended target.

The timings of stick-ball contact and ball release for the drag flickers were likewise determined in a previous study (Rosalie et al., 2018). The corresponding timings for the non-drag flickers were determined from the accelerometer data of the stick-mounted sensor using the same method. First, the data were filtered for impacts using a propriety filter (Delsys, EMGworks, Boston, MA, USA). The raw accelerometer data were high pass filtered at 10 Hz with a finite-impulse-response filter using a Blackman window and a kernel size of 127, rectified, then low-pass filtered at 5 Hz using a Blackman window and a kernel size of 127. Subsequently, the graphical representation of the impact trace was visually inspected for two characteristic peaks occurring in the axis parallel to the direction of stick ball contact corresponding to stick-ball contact and ball release (Jennings et al., 2010). The timings of the two impact peaks were checked for consistency with the high-speed video record. Drag time was calculated by subtracting the time of ball release from the time of stick-ball contact.

This study focused on the muscle activity of tibialis anterior, lateral gastrocnemius, and rectus femoris during the striking phase. The striking phase commences at stick-ball contact and concludes at ball-release. First, we trimmed the EMG record based on the previously determined timings of stick-ball contact and ball release and extracted the trimmed data for further processing using Delsys EMGworks. Next, we bandpass filtered the EMG data using a 4th order Butterworth finite infinite response (FIR) filter with corner frequencies of 20 and 500 Hz. Then, we calculated the time-dependent median frequency of the EMG power spectrum using a short-time fast Fourier transform with a window length of 0.125 s and a window overlap of 0.0625 s. Finally, we exported the median frequency (MF) data to SPSS (V25.0, IBM, NY, USA) for time normalization and max-min normalization data in preparation for statistical analysis.

Statistical Analyses

We used mixed effects growth models to analyze the normalized median frequency (NMF) data. We used a progressive modeling strategy as recommend by Singer and Willett (2003). This strategy has been used previously to examine muscle activity with respect to rehabilitation (Oskrochi et al., 2016) and sports performance (Rosalie & Malone, 2018a, 2018b; Rosalie & Malone, 2019). First, we fitted an unconditional linear model to the change in NMF over time. Then, we progressively added quadratic and cubic trends and selected the model with the best fit based on Chi-square likelihood ratio tests. Finally, we modeled the effect of individual differences by fitting a random intercept, a random slope, then a random intercept and random slope with a first-order autoregressive covariance structure that assumed that variances were heterogeneous. Again, we tested model fit using Chi-square likelihood ratio tests.

We then specified separate conditional models for tibialis anterior, lateral gastrocnemius and rectus femoris based on the unconditional model with the best fit. These models examined the fixed effects of skill specialization (drag flickers, non-drag flickers), shot speed, shot accuracy and number of shots taken on the change in NMF over time. We examined two parameters. Initial NMF, which corresponds to NMF at stick-ball contact and the rate of change (slope) in NMF which describes how NMF changes over time. Since EMG signals may be considered stationary during short-time intervals (0.5-2 s) (Phinyomark et al., 2012), these parameters were used as indices of muscle force at the stick-ball contact and the change in muscle force across the striking phase, respectively, with an increase in NMF indicative of an increase in muscle force (Cifrek et al., 2009; Phinyomark et al., 2012; Thongpanja et al., 2013). When compared over successive trials, these same parameters can be used an as index of fatigue with a downward shift in NMF indicative of fatigue (Cifrek et al., 2009; Phinyomark et al., 2012; Thongpanja et al., 2013). The alpha level was set at $p < .05$ for all analyses.

Results

Demographics

Independent t-tests revealed no significant differences between drag flickers and non-drag flickers except in the number of drag-flicks performed per week [$t(14) = 4.749$, $p < 0.001$].

Patterns of Muscle Activity During the Striking Phase

An unconditional linear model with a random intercept and a random slope with a heterogenous first-order autoregressive structure was the best fit for the data, $X^2 change\ (3) = 367$, $p < 0.01$. This model revealed that NMF was significantly predicted by linear time, $F(1, 9472) = 45.33$, $p < 0.001$.

Faster shot speed was associated with lower NMF of rectus femoris ($b = -0.36$, $t\ (1186.62) = -2.13$, $p = 0.03$) at stick-ball contact (Table 1). However, there was no significant effect for lateral gastrocnemius ($p = 0.75$) or tibialis anterior ($p = 0.11$). Regarding the linear slope of NMF, increasing shot speed had positive effects on the rate of change in NMF of rectus femoris (*b* = 1.51, *t* (1037.96) = 3.05, *p* = 0.002) and tibialis anterior (*b* = 1.48, *t* (45.35) = 2.82, *p* = 0.007). Rectus femoris NMF decreased across the striking phase for shots slower than 26.67ms^{-1} [40.27/1.51] (Singer & Willett, 2003) and increased across the striking phase for shots faster than 26.67ms^{-1} ($M_{shot\ speed}$ = 25.97ms^{-1}, *SD* = 2.90, Range: 14-35). Likewise, tibialis anterior NMF decreased across the striking phase for shots slower than 30.18ms^{-1} and increased across the striking phase for shots faster than 30.18ms^{-1}. However, shot speed was not associated with a significant effect on the linear slope of NMF of lateral gastrocnemius (*p* = 0.63).

Decreasing accuracy (increasing error) was associated with lower NMF of lateral gastrocnemius (*b* = -0.002, *t* (3190.46) = -1.97, *p* = 0.05) at stick-ball contact. However, there were no significant effects for rectus femoris (*p* = 0.10) or tibialis anterior (*p* = 0.27) at stick-ball contact. Regarding the linear slope of NMF, increasing accuracy score (i.e., the shot became *less* accurate) had a negative effect on the rate of change in NMF of lateral gastrocnemius (*b* = -0.008, *t* (3116.36). However, accuracy did not have a significant effect on the rates of change in NMF of either rectus femoris (*p* = 0.28) or tibialis anterior (*p* = 0.07).

Table 1. Estimates of the fixed effects of speed and accuracy on normalized median frequency (NMF) of the lateral gastrocnemius, rectus femoris, and tibialis anterior.

Muscle	Parameter	β	SE	df	*t*	*p*	95% CI Diff	
LG	Intercept	32.87	5.89	300.84	5.58	<0.001	21.28	44.47
	Time	1.20	17.57	352.90	0.07	0.946	-33.36	35.76
	Accuracy	-0.002	0.001	3190.46	-1.97	0.049	0.00	0.00
	Speed	-0.07	0.23	1014.27	-0.32	0.748	-0.52	0.38
	Time x Speed	-0.33	0.68	1081.64	-0.48	0.629	-1.67	1.01
	Time x Accuracy	-0.01	0.00	3116.36	-2.34	0.019	-0.01	0.00
RF	Intercept	24.86	4.46	244.49	5.58	<0.001	16.08	33.63
	Time	-40.27	12.78	334.14	-3.15	0.002	-65.41	-15.12
	Accuracy	-0.001	0.001	2996.39	-1.67	0.096	-0.003	0.000
	Speed	-0.36	0.17	1186.62	-2.13	0.033	-0.69	-0.03
	Time x Speed	1.51	0.50	1037.96	3.05	0.002	0.54	2.49
	Time x Accuracy	0.00	0.00	2902.78	1.07	0.283	0.00	0.01
TA	Intercept	38.79	5.44	137.76	7.13	<0.001	28.03	49.56
	Time	-44.67	13.27	56.19	-3.37	0.001	-71.26	-18.09
	Accuracy	0.00	0.00	1453.01	-1.12	0.265	0.00	0.00
	Speed	-0.33	0.20	193.90	-1.63	0.105	-0.72	0.07
	Time x Speed	1.48	0.52	45.35	2.82	0.007	0.42	2.53
	Time x Accuracy	0.01	0.00	366.90	1.80	0.072	0.00	0.01

Note. "LG" refers to lateral gastrocnemius, "RF" to rectus femoris, "TA" to tibialis anterior, "β" is the estimated effect size. "SE" is the standard error of β. "df" are the degrees of freedom. "*t*" is the standardized test score. "*p*" is the significance of standardized score. "95% CI" is the 95% confidence interval of β. "Intercept" refers to stick-ball contact. "Time" refers to the linear slope. "Skill" is the effect of specialization.

Patterns of Muscle Activity Across Trials

Table 2 shows the estimates of the fixed effect of trial on NMF at stick-ball contact and the change in NMF across the striking phase (i.e., Trial X Time). Trial had significant positive effects on NMF at stick-ball contact of rectus femoris (b = 0.35, t (3057.89) = 5.43, $p < 0.001$), lateral gastrocnemius (b = 0.24, t (3247) = 2.80, p = 0.05) and tibialis anterior (b = 0.46, t (3072.94) = 5.36, $p < 0.001$). Trial had a negative effect on the rate of the change in NMF of rectus femoris (b = -0.51, t (3059.73) = -2.59, $p < 0.01$) and a positive effect on the rate of change in NMF of tibialis anterior (b = 0.46, t (3072.94) = 5.36, $p < 0.001$). Trial did not have a significant effect on the rate of change of lateral gastrocnemius (p = 0.83).

Table 2. Estimates of the fixed effects of trial on normalized median frequency (NMF) of the lateral gastrocnemius, rectus femoris, and tibialis anterior.

Muscle	Parameter	β	SE	df	*t*	*p*	95% CI Diff	
LG	Intercept	32.87	5.89	300.84	5.58	<0.001	21.28	44.47
	Trial	0.24	0.09	3247.00	2.80	0.005	0.07	0.42
	Time x Trial	0.06	0.26	3250.13	0.22	0.826	-0.46	0.58
RF	Intercept	24.86	4.46	244.49	5.58	0.000	16.08	33.63
	Trial	0.35	0.06	3057.88	5.43	<0.001	0.23	0.48
	Time x Trial	-0.51	0.20	3059.73	-2.59	0.010	-0.89	-0.12
TA	Intercept	38.79	5.44	137.76	7.13	<0.001	28.03	49.56
	Trial	0.46	0.09	3072.94	5.36	<0.001	0.29	0.63
	Time x Trial	-0.91	0.26	2461.92	-3.48	0.001	-1.42	-0.40

Note. "LG" refers to lateral gastrocnemius, "RF" to rectus femoris, "TA" to tibialis anterior, "β" is the estimated effect size. "SE" is the standard error of β. "df" are the degrees of freedom. "*t*" is the standardized test score. "*p*" is the significance of standardized score. "95% CI" is the 95% confidence interval of β. "Intercept" refers to stick-ball contact. "Time" refers to the linear slope. "Skill" is the effect of specialization.

Skill Specialization

Table 3 shows the estimates of the fixed effect of skill on NMF at stick-ball contact and the change in NMF across the striking phase (i.e., Time X Skill). Skill did not predict NMF at stick-ball contact of either rectus femoris (p = 0.66), lateral gastrocnemius, (p = 0.11), or tibialis anterior (p = 0.64). Skill had a positive effect on the rate of change in NMF of tibialis anterior for drag flickers compared to non-drag flickers (b = 14.26, t (14.77) = 3.70, p = 0.002). However, there were no significant differences between drag flickers and non-drag flickers for the rates of change in NMF of either rectus femoris (p = 0.91) or lateral gastrocnemius (p = 0.58).

Individual Differences

Table 4 shows the results for the random effect tests for individual differences in NMF at stick-ball contact and the change in NMF across the striking phase. Results of the random effects test revealed that there was significant variation across individuals in NMF at stick-ball contact of lateral gastrocnemius, var(u_{0j}) = 18.76, p = 0.03, rectus femoris, var(u_{0j}) = 15.35, p = 0.02 and tibialis anterior, var(u_{0j}) = 27.14, p = 0.02. In addition, there was significant variation across individuals in rates of change in NMF of lateral gastrocnemius var(u_{1j}) = 151.50, p = 0.03 and rectus femoris var(u_{1j}) = 77.73, p = 0.03 but not tibialis anterior. Lastly, there was significant and negative covariation between NMF at stick ball contact and the rate of change in NMF across individuals for lateral gastrocnemius ρ = -0.6, p = 0.002 and tibialis anterior ρ = -0.93, $p < 0.001$ but not rectus femoris ρ = -0.4, p = 0.07.

Table 3. Estimates of the fixed effects of skill on normalized median frequency (NMF) of the lateral gastrocnemius, rectus femoris, and tibialis anterior.

Muscle	Parameter	β	SE	df	*t*	*p*	95% CI Diff	
LG	Intercept	32.87	5.89	300.84	5.58	<0.001	21.28	44.47
	Skill	-4.72	2.79	16.00	-1.69	0.110	-10.63	1.19
	Time x Skill	4.57	8.08	17.03	0.57	0.579	-12.48	21.63
RF	Intercept	24.86	4.46	244.49	5.58	0.000	16.08	33.63
	Skill	1.10	2.44	15.60	0.45	0.657	-4.07	6.28
	Time x Skill	-0.69	5.87	17.33	-0.12	0.908	-13.05	11.68
TA	Intercept	38.79	5.44	137.76	7.13	<0.001	28.03	49.56
	Skill	-1.53	3.20	14.85	-0.48	0.639	-8.35	5.29
	Time x Skill	14.26	3.86	14.77	3.70	0.002	6.03	22.49

Note. "LG" refers to lateral gastrocnemius, "RF" to rectus femoris, "TA" to tibialis anterior, "β" is the estimated effect size. "SE" is the standard error of β. "df" are the degrees of freedom. "*t*" is the standardized test score. "*p*" is the significance of standardized score. "95% CI" is the 95% confidence interval of β. "Intercept" refers to stick-ball contact. "Time" refers to the linear slope. "Skill" is the effect of specialization.

Table 4. Estimates of the random effect of individual differences in normalized median frequency of lateral gastrocnemius, recuts femoris, and tibialis anterior.

Muscle	Parameter	β	SE	Wald Z	*p*	*95% CI Diff*	
LG	Variance in intercepts	18.76	8.35	2.25	0.025	7.84	44.89
	Variance in slopes	151.50	67.51	2.24	0.025	63.26	362.83
	Covariance	-0.60	0.20	-3.03	0.002	-0.86	-0.09
RF	Variance in intercepts	15.35	6.50	2.36	0.018	6.69	35.19
	Variance in slopes	77.73	35.16	2.21	0.027	32.03	188.62
	Covariance	-0.45	0.24	-1.84	0.066	-0.79	0.11
TA	Variance in intercepts	27.14	11.49	2.36	0.018	11.84	62.22
	Variance in slopes	11.92	12.85	0.93	0.354	1.44	98.59
	Covariance	-0.94	0.25	-3.75	<0.001	-1.00	0.98

Note. "LG" refers to lateral gastrocnemius, "RF" to rectus femoris, "TA" to tibialis anterior, "β" is the estimated effect size. "SE" is the standard error of β. "df" are the degrees of freedom. "Wald Z" is the standardized test score. "p" is the significance of standardized score. "95% CI" is the 95% confidence interval of β. "Intercept" refers to stick-ball contact.

To determine the source of the variation, we conducted separate models for drag flickers and non-drag flickers (Table 5). These models were the same as the main models but excluded the main effects and interactions for skill and applied a scaled identity covariance structure. These analyses showed significant variation across individuals in the drag flickers group in NMF of lateral gastrocnemius, var($u_{0j} + u_{1j}$) = 102.68, $p = 0.01$, rectus femoris, var($u_{0j} + u_{1j}$) = 60.04, $p = 0.02$ and tibialis anterior, var($u_{0j} + u_{1j}$) = 11.17, $p = 0.03$. However, variation across individuals in the NDF group was not significant for NMF of either lateral gastrocnemius, var($u_{0j} + u_{1j}$) = 20.24, $p = 0.11$, rectus femoris, var($u_{0j} + u_{1j}$) = 11.94, $p = 0.16$ or tibialis anterior, var($u_{0j} + u_{1j}$) = 30.72, $p = 0.16$.

Table 5. Estimates of the random effect of individual differences on the intercept + slope of normalized median frequency of lateral gastrocnemius, recuts femoris, and tibialis anterior for drag flickers (DF) compared to non-drag flickers (NDF).

Muscle	Group	β	SE	Wald Z	*p*	*95% CI Diff*	
LG	DF	102.68	41.87	2.45	0.014	46.18	228.35
	NDF	20.24	12.69	1.59	0.111	5.92	69.19
RF	DF	60.04	24.64	2.44	0.015	26.86	134.21
	NDF	11.94	8.49	1.41	0.159	2.97	48.07
TA	DF	11.17	5.02	2.23	0.026	4.63	26.95
	NDF	30.72	21.70	1.42	0.157	7.69	122.67

Note. "LG" refers to lateral gastrocnemius, "RF" to rectus femoris, "TA" to tibialis anterior, "DF" to drag flicker and "NDF" to non-drag flickers. "β" is the estimated effect size. "SE" is the standard error of β. "df" are the degrees of freedom. "Wald Z" is the standardized test score. "*p*" is the significance of standardized score. "95% CI" is the 95% confidence interval of β. "Intercept" refers to stick-ball contact.

Discussion

Our first major finding was that shot speed was associated with muscle activities of rectus femoris and tibialis anterior but not lateral gastrocnemius. Although faster shots were associated with lower activity of rectus femoris at stick-ball contact, NMF of rectus femoris increased across the striking phase for shots faster than $26.67 ms^{-1}$ (i.e., shots with above average speed). Activity of rectus femoris decreased across the striking phase for shots slower than $26.67 ms^{-1}$ (shots of approximately average speed or less). In contrast, activity of tibialis anterior only increased across the striking phase for the fastest shots, those above $30.18 ms^{-1}$ and decreased for shots slower than $30.18 ms^{-1}$. Given that the lead lower limb kinematics of this group of players does not predict drag-flick speed (Rosalie et al., 2018), these results were probably due the roles that these two muscles play in trunk kinematics. Rectus femoris is thought to directly generate throwing velocity by flexing the trunk at the hip (Matsuo et al., 2001; Morriss & Bartlett, 1996). In baseball batting, greater activity of tibialis anterior improves stance stability (Feger et al., 2014) leading to a more effective swing (Nakata et al., 2013). Therefore, high drag flick speed depends on both power output from hip flexors muscles and the ability of ankle dorsiflexors to stabilize stance during the striking phase.

Our second major finding was that only lateral gastrocnemius had an important role in determining shot accuracy. Less accurate drag-flicks (i.e., increased accuracy score) were associated with both a lower index of muscle force at stick-ball contact and a smaller increase in the index of muscle force across the striking phase. Again, this was likely due to a role in stabilizing stance (Feger et al., 2014). Consequently, accurate drag flicks depend on ankle plantar flexors to stabilize stance.

Our third major finding was that despite using a work-rest ratio specifically designed to prevent fatigue, number of shots taken predicted muscle fatigue. As trial number increased, NMF at stick-ball contact increased for all three muscles. One possible explanation is that as the players took successive shots, they became more familiar with the experiment task and “hit the ball harder” resulting in increases in indices of work force production at stick-ball contact for rectus femoris, lateral gastrocnemius, and tibialis anterior. To confirm whether shot speed increased over success trials, we conducted a follow up linear mixed model.

The results of this model showed that as trial number increased shot speed decreased. Therefore, it is more likely that the increases in NMF at stick-ball contact were a consequence of fatigue. Presumably, as Type IIb fibers fatigued over successive shots decreasing their ability to produce force, players recruited more larger fibers of higher conduction velocity to maintain shot speed thereby increasing median frequency (Kupa et al., 1995). Certainly, the negative effect of trial on the slope of rectus femoris is also consistent with fatigue. However, the positive effect for tibialis anterior is not, although tibialis anterior has a low percentage of Type II fibers (Johnson et al., 1973). This may reflect a greater need for tibialis anterior to stabilize stance as other muscles fatigued after repeated efforts.

From the perspective of skill performance, much like our previous studies of this group of players (Rosalie et al., 2017; Rosalie et al., 2018), the differences between the individual drag flickers were more striking than the differences between the drag flickers and the non-drag flickers. Patterns of muscle activation of lateral gastrocnemius, rectus femoris, and tibialis anterior all varied between drag flickers but none of the corresponding patterns varied between non-drag flickers. It seems that individual differences in the drag-flick speed of specialist drag flickers (Rosalie et al., 2017), is coupled more tightly to individual differences in patterns of muscle activation than to the resulting kinematic patterns (Rosalie et al., 2018). In contrast, differences in shot accuracy between specialist drag flickers is coupled to individual differences in both patterns of muscle activation and kinematics (Rosalie et al., 2018). While for non-drag flickers, the lack of individual differences in their patterns of muscle activation in the lead lower limb corresponds with the absence of individual differences in shot accuracy (Rosalie et al., 2017). However, it does not explain differences in shot speed between non-drag flickers (Rosalie et al., 2017).

Presumably, differences in shot speed between non-drag flickers arise from muscles other than those sampled here. Interestingly, the rate of change in muscle force of tibialis anterior was the parameter most closely related to skill specialization. The decrease in tibialis anterior muscle force across the striking phase was much smaller for the drag flickers compared to the non-drag flickers. Studies of baseball batting have found that skilled baseball players also have greater activation of tibialis anterior than unskilled players, particularly later in the striking phase (Nakata et al., 2013). Again, this is probably due to the role that tibialis anterior plays in stabilizing stance.

The method that we used to determine shot speed was the major limitation of our analysis of skill performance. Rather than calculating average horizontal flight speed from the point of ball release which varies shot-by-shot due to differences in flight distance (Ladru et al., 2019; Rosalie et al., 2018), we used the known and constant distance of 14.63m. Accurate measurement of flight distance from ball release to target impact cannot be achieved using only one camera. Rather, this could be achieved only by using at least two orthogonally arranged cameras capturing a calibrated volume; this was not possible in the setting of an open hockey field.

From the perspective of injury prevention, variability between individual drag flickers’ patterns of muscle activation have significant implications. Being able to vary movement patterns helps to prevent injury, particularly overuse injuries (Bartlett et al., 2007). Researchers have identified that reduced variability in joint coordination (Hamill et al., 1999; Heiderscheit, 2000; James et al., 2000) and repetitive loading of the same tissue (Bradshaw et al., 2009; Bradshaw et al., 2007) increase injury rate. However, despite the activation patterns of lateral gastrocnemius, rectus femoris, and tibialis anterior being more variable for drag flickers compared to non-drag flickers, they remain more susceptible to injury.

There are three possible explanations. One, the root cause of drag flickers' higher prevalence of hip and lower back injuries (Ng et al., 2016) is not related to the patterns of muscle activation of the three muscles we examined. Two, the kinematics of the drag-flicking action itself is the root cause. Three, the root cause does not occur relate to the biomechanics of the striking phase. The latter represents the main limitation of this study. Our analysis was restricted to patterns of muscle activation occurring within the short time window between stick-ball contact and ball release (i.e., the sticking phase). It is entirely plausible that pre-striking phase or the follow-through could be the source of hip and lower back injuries in drag flickers. For example, in golf peak upper torso angular velocity occurs during follow-through and is much higher for professionals compared to non-professionals which is thought to have implications with respect to injury (Steele et al., 2018). In addition, the contemporary understanding of injury and pain acknowledges the contribution of psychosocial factors (Williams & Andersen, 2007) which were not considered in this research.

Conclusion

To the best of our knowledge, this is the first study to investigate muscle activity during the striking phase of the drag-flick. We have shown that patterns of muscle activity vary between drag flickers but not non-drag flickers, that differences between skill groups are related to stabilization of stance which affects accuracy, and that speed is related to both stability and the role of lower limb muscles in moving the trunk. Further research should both extend the range of muscles sampled and examine muscle activity during an actual game to give more information about the relationship between patterns of muscle activation and both performance and injury.

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Authors' Declarations

The authors declare that there are no personal or financial conflicts of interest regarding the research in this article.

The authors declare that they conducted the research reported in this article in accordance with the Ethical Principles of the Journal of Expertise.

The authors declare that they are not able to make the dataset publicly available but are able to provide it upon request.

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