Kinematic Analysis of Phase-Specific Cued Stopping in Fencing Footwork Advances

Spencer McGregor
Department of Applied Human Sciences
University of Prince Edward Island
Charlottetown, PE, Canada

A thesis submitted in partial fulfillment of the requirements of the Honours Program in the Department of Applied Human Sciences

This Thesis is Accepted

____

Dean of Science
University of Prince Edward Island

May 2018

Abstract

Background: Kinematic analyses of fencing footwork have been scarce in the literature, and studies on stopping in fencing are essentially non-existent. Despite this, stopping plays a critical role in fencing ability as it pertains to mobility and direction change. Purpose: The aim was to identify differences between stopping behaviour as a function of the footwork phases fencers occupied when presented with a stop cue. The objective of this research was to lay the foundation for future studies to analyze fencing footwork, with the ultimate goal of generating data driven recommendations for improved sport performance. Methods: This study used a descriptive design. Fencers (n.4) performed forward fencing specific footwork to the beat of a metronome set to 120bpm. Participants were asked to stop as quickly as they could when they saw the visual cue, which was a white computer screen with the word STOP in red letters. An Optotrak motion capture system was used to track the motion of two rigid bodies place on the feet. The Optotrak system included two 3D cameras, and the rigid bodies were created from a set of three IRED markers placed non-colinearly on a thin acrylic triangle. Results: Result suggest there are differences between footwork stopping behaviour as a function of the four footwork phases analyzed (front foot swing (FS), front foot contact (FC), back foot swing (BS), and back foot contact (BC). Trials where fencers occupied FS at the time of cue presentation were found to result in the slowest stop, while those in BS were found to stop most quickly. Conclusion: Despite preliminary evidence suggesting a difference between stopping behaviour as a function of footwork phase, significance has not been established, and explanations of the causes of any differences are speculative.

Table of Contents

List of Tables

List of Figures

INTRODUCTION

Fencing is a combat sport where the objective is to make contact with the opponent using one of three fencing weapons: the foil, the epee, or the sabre. Each discipline has its own set of rules and techniques, but common to all is the objective to hit the opponent with the blade, either with the tip or the edge depending on the weapon, without getting hit.

Fencing is performed on a 14 meter long and 1.5 to 2 meter wide rectangle called a piste or strip, as shown in Figure 1. There is little room to move side to side, so the footwork in fencing must therefore be suited to a linear boundary. Fencing begins with a stance called the en garde position that requires the fencer to hold their sword arm in a slightly extended position with the elbow tucked in close to the trunk, and with the legs positioned one in front of the other with the front leg being the same side as the sword arm, and the back leg turned outward at about a 90 degree angle. The knees should have a moderate bend, the feet should be spread a little wider than shoulder width apart, and the upper body should be turned to face forward towards the opponent. Figure 2 shows a form of the en garde position.

The fencer in Figure 2 has a very strict version of the en garde position, specifically with the back hand being held above shoulder level, and the knees having a deep rather than moderate bend. However, it is a very good example to draw attention to the key aspects of the position, namely the placement of the feet.

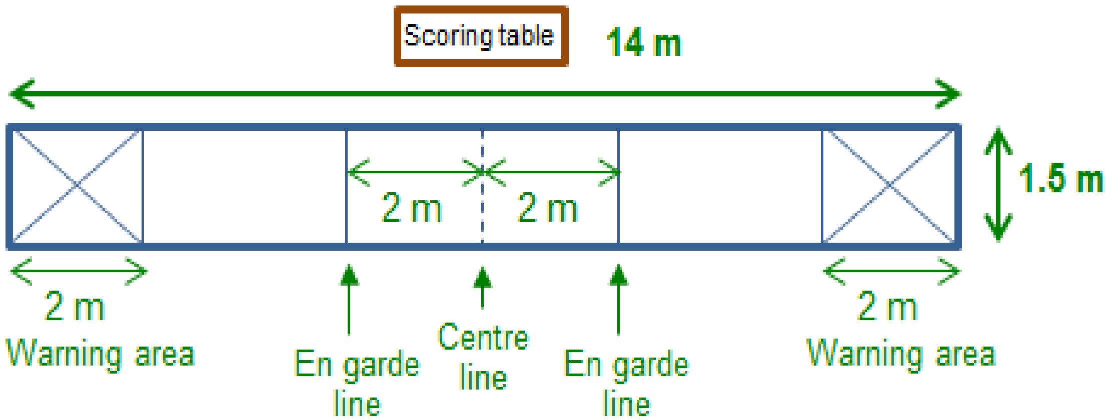

Figure 1. Fencing piste dimensions (Pope Greyhound Fencing Club, 2018).

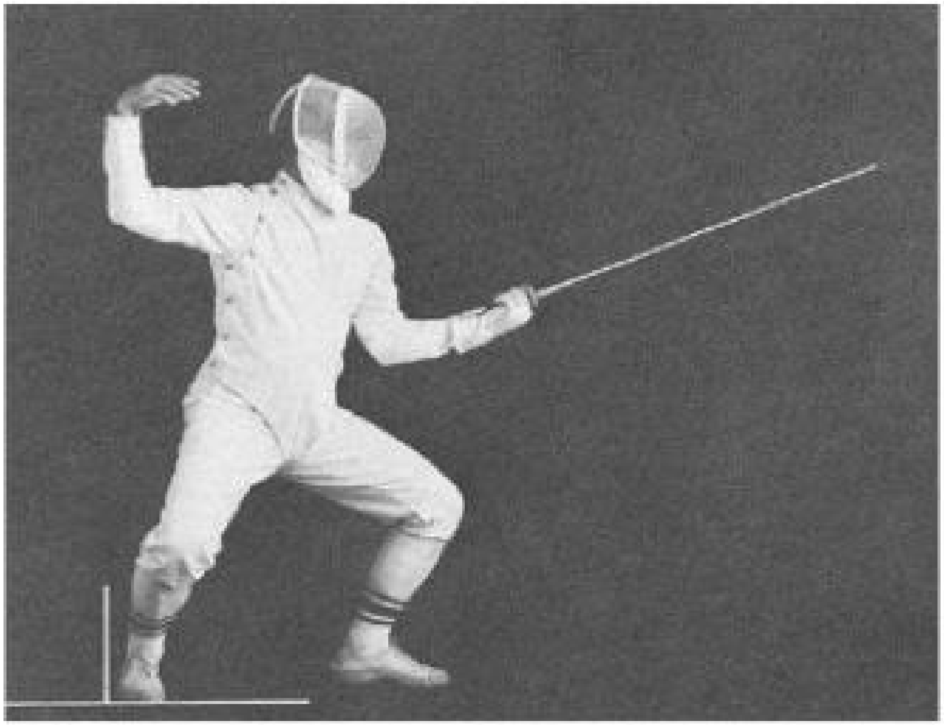
Figure 2. Proper en garde position (Martial Arts Beta, 2016).

While there are variations among fencers as to the angle between the front foot and the back foot, most fencers come close to the 90 degree angle presented in Figure 2. Because the en garde position is the standard position in fencing, it informs all other movements, hence determining the type of locomotion a fencer can use.

Typical walking gait involves two main phases, stance and swing. Stance phase begins with heel strike, followed by mid-foot contact, ends with heel-off. Total stance for a single leg typically comprises 60.2% of gait in healthy young adults, while double support typically spans 22.8% of the gait cycle (Agostini, Balestra, & Knaflitz, 2014; Malatesta, Canepa, Menendez Fernandez, & Canepa, 2017; Tasuku, Hiromitsu, Eijun, & Michiko, 2007). Swing phase begins when the whole foot leaves the ground in toe off, which is followed by early swing, midswing, and late swing phases (Schulz, 2017). Swing phase for a single leg typically comprises 39.8% of the gait cycle (Tasuku, Hiromitsu, Eijun, & Michiko, 2007). Fencing footwork shares most of these phases, but their relative duration is currently unknown. As well, the main difference between gait and fencing footwork is that the trailing leg never crosses in front of the leading leg (Malawski & Kwolek, 2016). The other difference is the back leg is externally rotated around 90 degrees relative to the front leg. To advance in fencing, the fencer must pick up the front foot by elevating the heel and toes, and extending out the front leg until the heel of the front foot makes contact with the floor. The order of which is elevated first, the toes or the heel, differs between fencers. After this the back leg follows by bringing the back heel off the ground followed by the toes, and moving the back foot closer to the front foot, but not crossing in front of it, and finishes by making contact with the floor, typically beginning with the toes or midfoot and then the heel. Figure 3 shows this process in four simplified phases which are done in a cycle to keep moving forward. To retreat, the same process happens in reverse, with the back foot extending back first, followed by the front. The distance between the feet at the end of the step should be the same as the starting position. There should be very little movement of the upper body throughout the step.

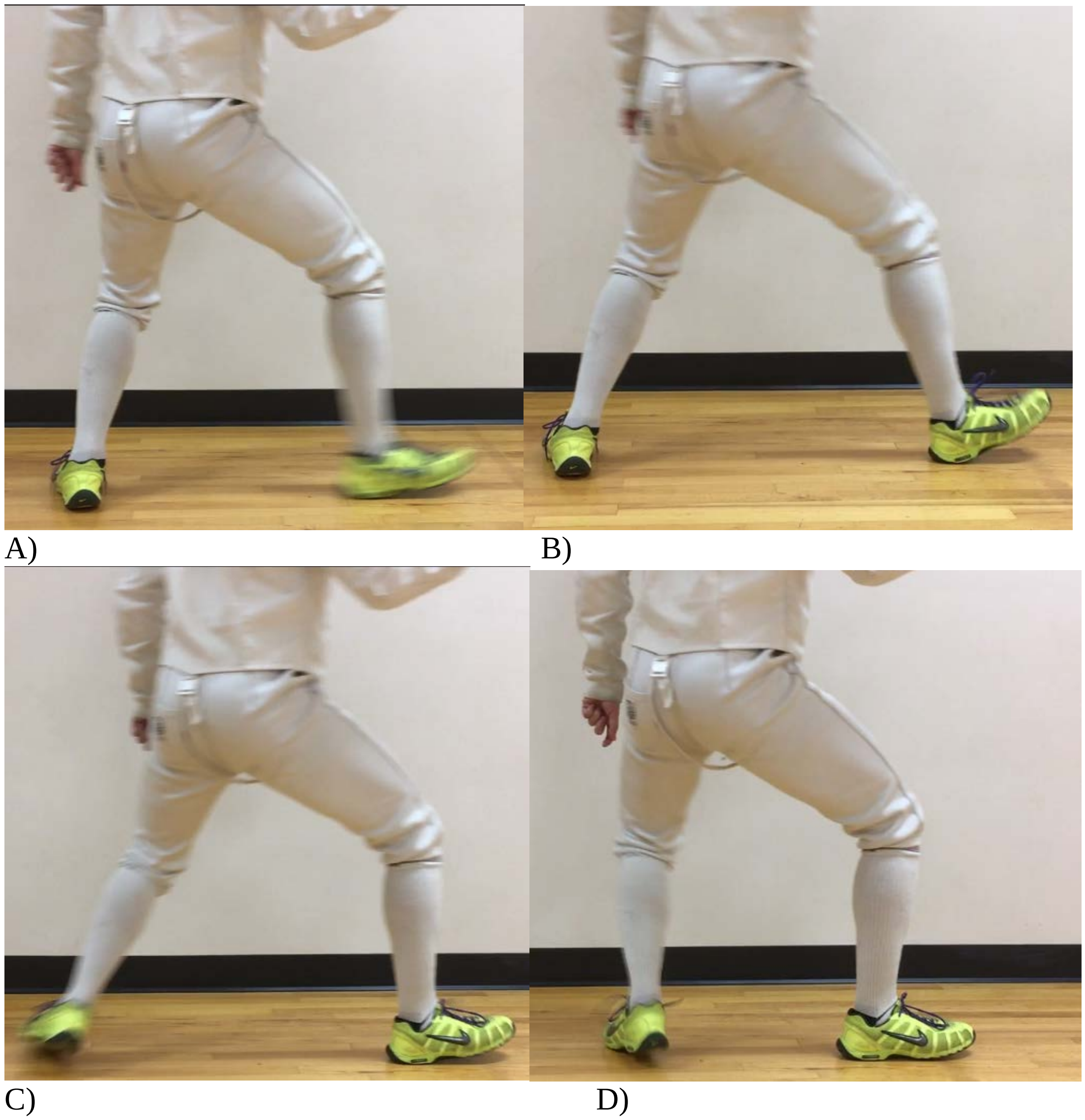

Figure 3. Example of one complete advance in fencing including the four footwork phases: A) Front Foot Swing (FS), B) Front Foot Contact (FC), C) Back Foot Swing (BS), and D) Back Foot Contact (BC).

The blade of a fencing weapon is commonly said the be the second fastest moving object in sport, with only the marksman's bullets being faster. Despite the questionable validity of this statement, it is clear that minute differences in footwork proficiency can play a dramatic role in performance. Therefore, being able to quickly change between moving forward and backward is of utmost importance to fencers. The reason for these changes of direction is to attempt to reach a distance the fencer judges to be most optimal in that instance, whether that be for offensive or defensive reasons. In a review of fencing literature, Roi and Bianchedi (2008) found that fencers in international competitions changed directions an average of 200 times per match (Roi & Bianchedi, 2008). In each of these changes of direction, a fencer must decelerate, come to a stop, and accelerate in the other direction. Although fencers do this seamlessly in a matter of milliseconds, there will inevitably be a point where the fencer's center of mass is stationary. Therefore, stopping can be viewed as one of the most pivotal movements in fencing, and learning more about how stopping is performed could lead to insights that could significantly improve a fencer's performance.

Despite the importance of stopping to fencing performance, there has been very little research looking at stopping directly. Moreover, previous research on fencing footwork in general is limited, and the studies that exist have focused on other factors as their main priority.

Literature review

The most prominent studies on fencing footwork have looked at describing the prevalence and factors associated with injury rates (Roi & Bianchedi, 2008), the associations between change of direction speed and physical characteristics such as jumping ability (Turner et al., 2016), the effects of various athletic shoes on footwork kinematics and their role in dissipating plantar foot pressures (Geil, 2002), and the use of dynamic time warping and a support vector machine to classify various fencing actions (Malawski & Kwolek, 2016). There appears to be a gap in the literature surrounding the fundamental analysis of the kinematic factors relating to the performance of footwork actions. Specifically, kinematic variables such as the relative and absolute duration of each footwork phase, the timing of the phases, general stopping patterns, and whether occupying a particular phase plays a role in a fencer's ability to stop optimally have yet to be tested.

In order to fill this gap in the literature, a study would need to include both an analysis of stepping patterns, and explore how particular points in fencing footwork influence stopping. However, before studying stopping patterns it is first necessary to understand the context in which stopping occurs. Stopping is understood to be a critical portion of distance control, which is assumed to be heavily influenced by the movement by the opponent. Therefore, stopping can be framed as a responsive action, which can be measured in terms of response time. Consequently, response time is a critical component to stopping, and thus fencing ability. Response time is defined as the total time it takes to react to a stimulus, from stimulus presentation to response completion (Schmidt & Lee, 2011). Response time includes reaction time, the time it takes from the presentation of a stimulus until initiation of the motor response, and movement time, the duration of the motor response from start to finish (Schmidt & Lee, 2011). In the cognitive theoretical framework, humans are processors of information, and the processes involved in interpreting stimuli and planning motor behaviour are integral to motor execution (Schmidt & Lee, 2011). reaction time is dependent on the information processing stages of stimulus identification, response selection, and response programming (Schmidt & Lee, 2011). Stimulus identification is comprised of stimulus detection, the perception of environmental information by sensory organs, and pattern recognition, the processing of that information in the brain until that information is recognized in the person's memory of past experiences (Schmidt & Lee, 2011). Response selection is the decision of which motor program will be initiated based on the external information and the context in which it appears (Schmidt & Lee, 2011). It is influenced by the number of alternatives available, the compatibility of the stimulus and the response, and the previous experience with the stimuli (Schmidt & Lee, 2011). Finally, response programming is the organization of motor signals in the brain, the transmission of these signals through motor neurons, and their reception in the final effector organ, specific muscles (Schmidt & Lee, 2011). This primes the muscles involved to execute the chosen motor program (Schmidt & Lee, 2011).

It has been shown that training athletes to better interpret an opponent's postural and movement cues leads to improved anticipation and reduced reaction time (Powell, 2001). However, the reliance on early postural cues does not appear to be substantial in actual sport contexts. A study by Triolet et al. (2013) showed that professional tennis players chose to delay beginning their motor response until an average of 200ms after the opponent had struck the ball. Anticipatory responses, meaning motor responses that began before the ball was struck occured between 6.14 and 13.42% of the time, while reactionary responses, meaning those that began after the ball was struck occurred the other 86.58 to 93.86% of the time (Triolet, Benguigui, Le Runigo, & Williams, 2013). Triolet et al.'s (2013) study analyzed videos of professional tennis players during several world ranking tournaments. The player's action was said to be initiated at the first frame where the player exhibited "an observable and significant lateral motion … of the racket, the hips, the shoulder, or the feet" (Triolet, Benguigui, Le Runigo, & Williams, 2013). This frame was compared to the first frame where the opponent struck the ball. Anticipatory responses were determined to be made if the player moved before the ball was struck or before 60ms after the ball was struck, hence the range in values. Up to 60ms after the ball was struck was considered anticipatory based on minimum reaction time data. Triolet et al. (2013) analyzed these motor responses in several contexts, including three court style (grass, clay, or hard court), and either favourable or unfavourable positions of the players on the court specific to the context of the play. They found the only situations where players used predominantly anticipatory responses were during unfavourable situations, where they had less time to react.

Initiating an anticipatory response inherently means acting earlier than a reactive response, which is preferable in situations where fast reactions are imperative, such as in tennis. It would follow that anticipatory responses ought to be favourable in the whole sport context, everything else being equal. However, while anticipatory action have the potential to decrease reaction time (Powell, 2001), professional tennis players still predominantly relied on reactive actions. This is attributable to the differences in the use of the information processing stages between anticipatory and reactive responses. Anticipation inherently means to act before all the information is available. In terms of information processing, this means anticipatory responses neglect the stimulus identification stage. This leads to players relying solely on contextual, rather than perceptual information to determine the correct response during the response selection phase. In situations where several outcomes may occur, such as the opponent making different shots in tennis, anticipatory responses lead to reduced accuracy in response selection. This can also be seen in Triolet et al.'s (2013) study, where anticipatory responses resulted in decreased accuracy of up to 30% compared to reactive responses (Triolet et al. 2013). It can therefore be said that athletes rely predominantly on reactive responses due to the increased accuracy stimulus identification offers for response selection, at the expense of earlier reactions that occur from anticipatory responses.

In tennis, accuracy is arguably more important than speed, or at least this appears to be supported by Triolet et al. (2013). However, it is imperative to test if the same trend appears in fencing if we are to understand what determines a fencer's choice to stop. A study by Gutierrez-Davila et al. (2016) explored when elite fencers would begin a retreat (a step back) when a fencing master performed a lunge or a feint lunge. A fencer and a fencing master stood in the en garde position facing each other. The fencing master was cued by a LED light by the researchers (not visible to the defender) to begin a lunge or feint lunge. The fencer was instructed to step back as quickly as they could to avoid getting hit once they saw the fencing master's attack. The delay until the fencers began their reaction was recorded starting from the point of just noticeable difference (JND) of the attacker's position. The JND was determined to be the difference between the time the fencer began their motor response and their recorder reaction time. They found that fencers began their response 0.239s after the lunge began, and 0.243s after for the feint lunge (Gutierrez-Davila, Rojas, Gutierrez-Cruz, Garcia, & Navarro, 2016). Similar to Triolet et al. (2013) this study showed reactive motor responses to an opponent's action. However, the parameters of the study specifically required the fencers to remain in a static position until they perceived an attack, meaning there was no incentive to response earlier. Gutierrez-Davila et al. (2016) included a second portion of the study where the fencers were instructed to retreat when they saw a LED light on the master's bib instead of an attack, which would have given an indication on whether pre-attack postural cues influenced fencers' response execution, however these trials were used as the basis for establishing the JND values and were not compared to attack trials. Therefore, little can be said about this study in terms of indicating preference for anticipatory or reactive responses in fencing. Furthermore, the study was done with fencers in a static position, which is not representative of the majority of fencing. Therefore, subsequent studies should control for anticipatory information to determine its contribution, as well, studies should use a dynamic experimental setup which includes fencing specific footwork to better simulate fencing. Additionally, if a dynamic set-up were utilized, it would be ideal to determine if there are differences in how fencers react depending on where in their footwork they are cued.

The draw back of a dynamic design is that it is more difficult to determine the relative contribution of reaction time and movement time to total response time. Unlike static designs where reaction time is defined as the time between motionless and moving portions of the response, dynamic designs have to define the transition between reaction time and movement time with statistically different trajectories of movements because movement is happening in both portions. Alternatively, this issue can be overcome if reaction time is found to be statistically equivalent in all study conditions.

Hick's law describes a logarithmic increase in reaction time when the number of response options doubles (Wifall, Hazeltine, & Mordkoff, 2016). This can be shown in the context of fencing in the study done by Gutierrez-Davila et al. (2013), which tested reaction differences between a 2 and 4 option target change task. The participants were instructed to perform a lunge to hit a projected target on a plastron (a piece of fencing equipment). There were two of these plastron targets, one which would change the target location between two points, and one which would change the target location between four points. The time at which the target change occured was kept consistent. The researchers found that choice reaction time, defined as the time take to change the weapon trajectory to the appropriate target was longer in the 4 option condition: 243ms +/- 44ms compared to 186ms +/- 46ms. Therefore, reaction time can not be considered statistically equivalent in contexts where variable response options are present.

However, in contexts where a constant number of response options is present, some research suggests reaction time is much more stable. Gutierrez-Cruz et al. (2016) explored the relationship between early and late cueing on reaction time, movement time, and various kinematic metrics using a constant number of response options. Specifically, they looked at the effect of target uncertainty on movement time and simple and choice reaction time. They used a very similar setup to Gutierrez-Davila et al. (2013) but only used a 4 option display and varied target change time. They instructed fencers to perform a step lunge with the intent to hit a projected target on plastron. The researchers selected four different points during the attack at when the target could change location. They found that movement time was increased with delayed target change, associated with increased uncertainty. However, they found that choice reaction time, which was defined as the difference between when the target changed and when the fencer altered their weapon's trajectory, was not statistically different for three out of the four conditions. The only condition where choice reaction time was found to the statistically different was during the earliest target change, where the fencer took longer to change their trajectory. This difference was attributed to a lack of time pressure due to the increased time the fencer had available before making contact with the target. Therefore, choice reaction time did not appear to be influenced by the phase of the fencer's action. This supports the validity of the assumption that reaction time would not be influenced by occupying different phases of gait, and so reaction time can be assumed to be statistically equivalent in this context. Critically, this would indicate that any differences between the response time for different phases would be attributable solely to the movement time.

Based on the current body of information, it is unknown whether the same preference for reactive rather than anticipatory responses that exists in tennis also exists in fencing. Without this information studies aiming to understand footwork and stopping should seek to limit the availability of anticipatory information using cues such as coloured lights, discrete sounds, or discrete tactile sensations. Such studies may benefit from the findings of Gutierrez-Cruz et al. (2016), which indicated that differences in response time between various phase conditions of a movement are attributable to the differences in movement time alone. This alleviates the need for complex statistical analyses to distinguish between the relative contribution of reaction time and movement time to response time.

In order to properly describe footwork and stopping, it is important to simulate realistic fencing contexts. Evidently, describing footwork and stopping will require a dynamic approach that involves the participant performing footwork before they are required to respond to a stimulus and, consequently, stop. It is also necessary to randomize cue presentation to simulate uncertainty in the sport context. To capture the full effect of a randomized cue, it is necessary to present cues during different phases of the footwork cycle. As previously stated, the critical metric of stopping performance is response time. It is therefore important to evaluate the influence of the phases themselves on response time.

Purpose

The following experiment uses a descriptive analysis design aimed to describe the impact of footwork phase on stopping response time. Footwork phase refers to the position in the fencer's footwork cycle they occupy at a given moment. In this study, the footwork cycle for fencing is broken down into four distinct phases: front foot swing, front foot contact, back foot swing, and back foot contact. These phases are shown in order in Figure 3. Specifically, this study describes whether there are points during the fencing footwork cycle when movement time to achieve a stop is shorter or longer, leading to a better or worse ability to respond optimally to an attack. This knowledge could lead fencers and coaches to pursue new tactical and technical training that may improve performance. To supplement the data on movement time, this study analyzed three other kinematic variables, namely fencers' post-cue step number, the difference between actual and expected stop time with reference to foot contact, and the duration of time spent in each phase. Stopping was defined here as the complete cessation of forward velocity from an initial condition of forward progression of the whole body, but with particular reference to the feet. It was hypothesized that fencers would take longer to stop if a stop cue was given during swing phases rather than contact phases. This hypothesis assumed that a foot in swing would require additional time to generate a braking force to achieve a stop because it would have to first regain contact with the floor. It was also hypothesized that post-cue step number and differences between real and expected movements would change depending on when the stimulus is given. Our final hypothesis was that each phase with last approximately the same amount of time.

METHODS

Participants

Participants were recruited from the UPEI Fencing Club (n.=4, mean age 16.5+/-1.5 years). The head researcher went to a regular practice session and determined the most prevalent cohort of fencers. He then asked fencers within this cohort of age and experience level if they wanted to participate in the study. The head researcher explained what the research entailed and what the participants would do. The largest cohort was found to have an age range of 13 years old to 20 years old, and an experience level between 4 months and 2 years. This set the basis for the inclusion criteria. The inclusion requirements attempted to reduce skill variability which increases the likelihood that the results accurately reflect fencers' experience level performance, in this case at a novice skill level. The researcher provided consent forms and information sheets to those eligible fencers interested. The respondents ended up being much more tightly clustered in terms of skill level and experience than the inclusion requirements specified. All fencers who participated in the study had experience levels between 5 to 6 months when the study was conducted, and had ages ranging from 15 to 18 years. Once the participants had been contacted and had completed the required forms, they came into the lab individually. The researcher explained what they would be doing for the test, and answered any questions they had about the study. Human subject ethics approval was obtained from the UPEI ethics board prior to experiment.

Experimental setup

The lab was a well lit room with plainly coloured walls with no visually distracting items such as posters in the view of participants. There was a starting line of tape on the floor which the participant stood behind in the en garde position while waiting for the trial to start. There was a 13 inch computer monitor set 4 meters away from the start line, directly in front of the visual field of the participant (Figure 4). The computer monitor featured a black screen with the word “Ready?” in white print initially (Figure 5), which would change to a solid black screen during their steps (Figure 6), followed by a white screen with a large printed “STOP” written in red letters to cue the participant to stop moving at the appropriate time (Figure 7).

There was a digital metronome playing on the computer, but this was not visible (Xanin Tech., 2014). The audio of the metronome was set to a clearly audible volume in the otherwise quiet room. An Optotrak motion capture system was used, which included two 3D Investigator Position Sensor cameras, an Optotrak Certus System Control Unit, an Optotrak Wireless Prober, and several infrared light emitting diodes (Northern Digital Inc., 2013). One camera was positioned at the left side of the room facing 120 degrees from the forward reference point of the participant, and one was at the front of the room facing 30 degrees from the forward reference point of the participant. The cameras were set to a frame rate of 100 frames per second. They did not impede the participant from viewing the monitor, and the monitor did not impede the cameras from viewing the participant. The cameras were placed 3-4m away from the participant to allow for a large enough field of view to capture several steps. The cameras were designed to track a kind of marker that emits infrared light, referred to as an Infrared Light-Emitting Diode (IRED). The Optotrak system recorded the position and orientation of these markers across time. Three IRED markers were anchored to a rigid acrylic triangle and then placed non-colinearly to form a triangle, as shown in Figure 8. This ensured that the markers stayed a constant distance from one another, which allowed researchers to create a three dimensional representation of the markers as an object, called a rigid body.

Figure 4. Photo of the experimental setup including the computer monitor, the distance to the computer monitor as captured from the point of view of a fencer, and one of two 3-D cameras.

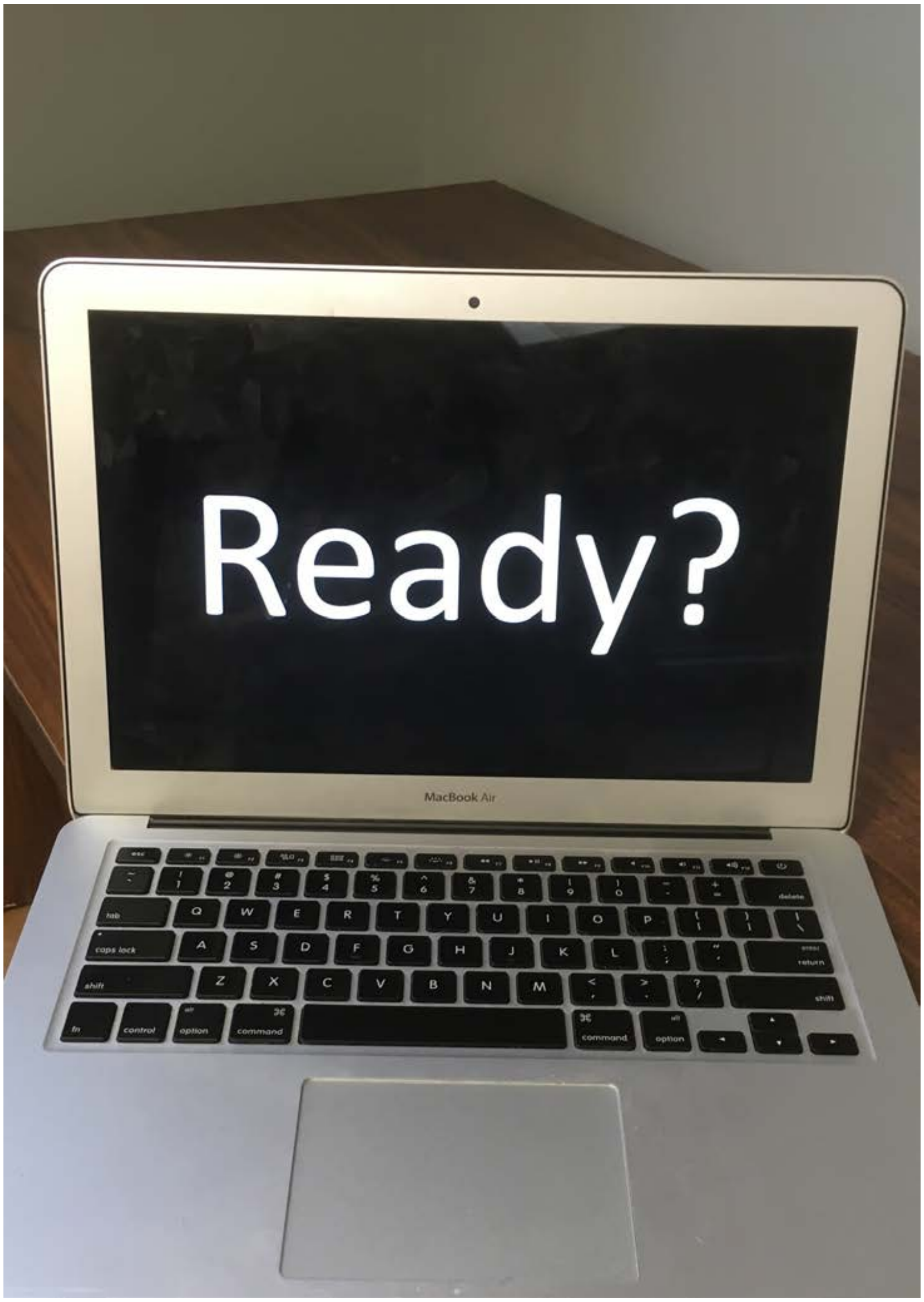

Figure 5. "Ready" screen shown before trials.

Figure 6. Black screen shown during trials.

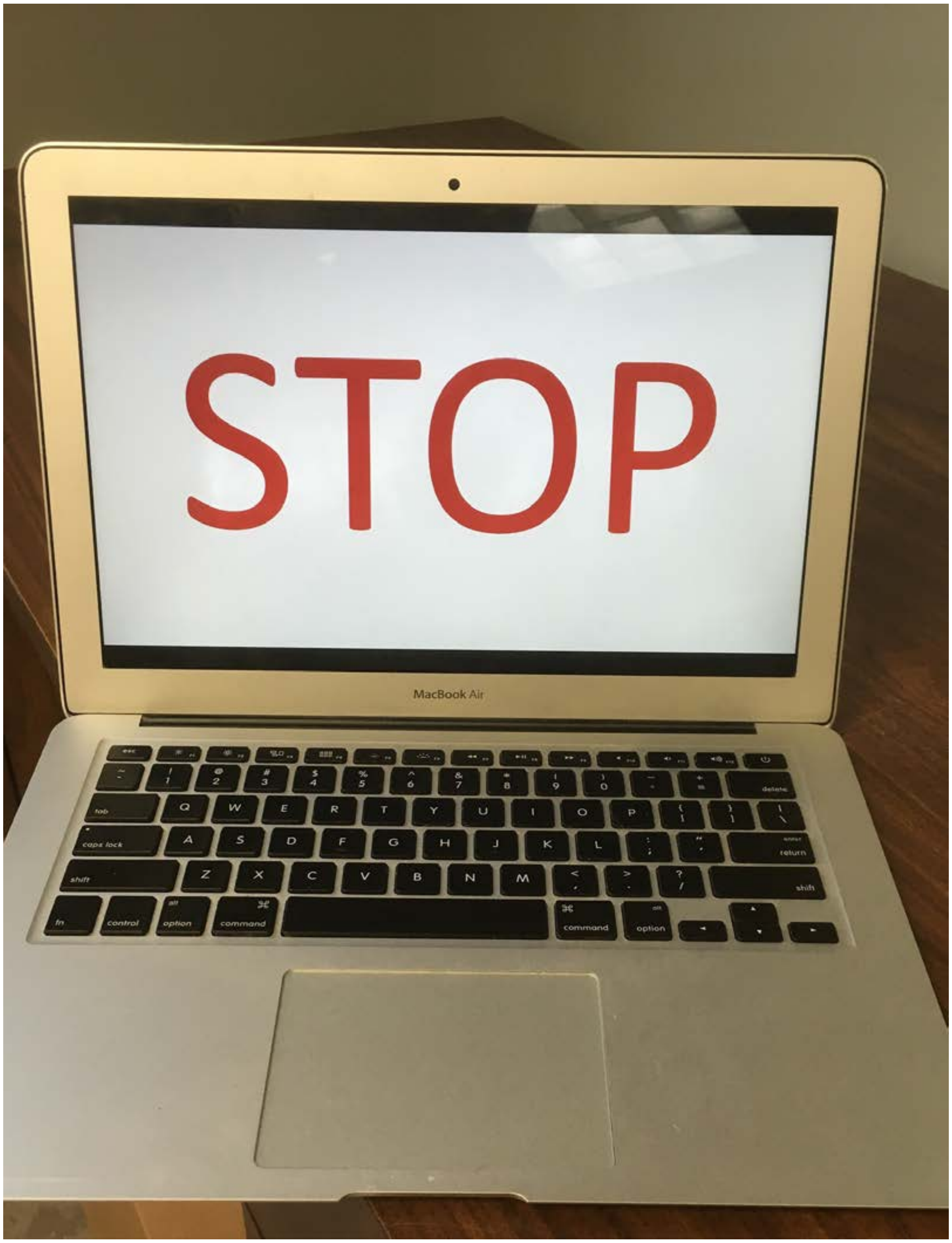

Figure 7. “STOP” screen shown at the end of trials.

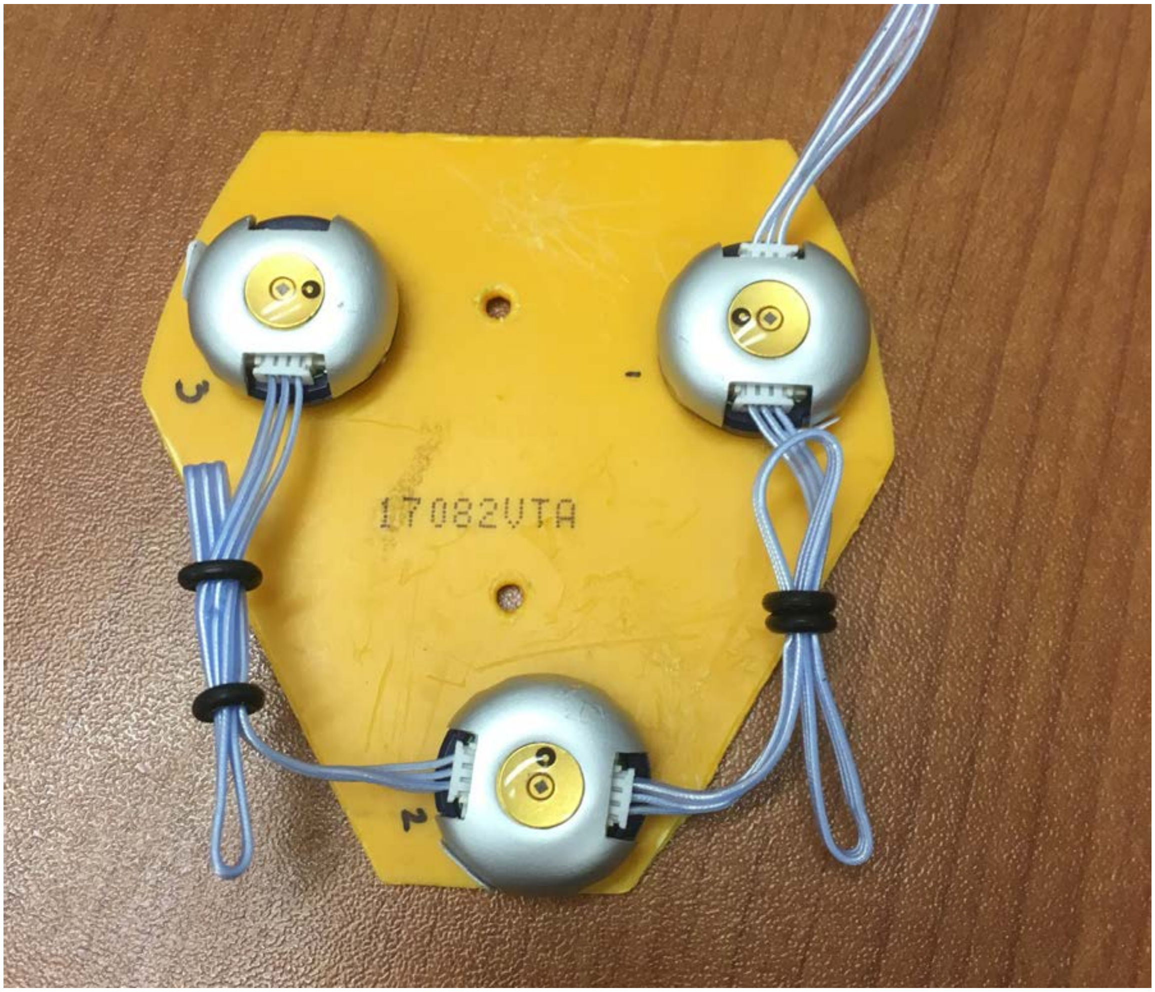

Figure 8. Example of a rigid body.

This enabled researchers to digitize anatomical landmarks on the participant's body that remained a constant distance from the rigid body. The rigid bodies were placed on the upper foot. The digitized landmarks were the heel, the big toe, and the 5th metatarsal as shown in Figure 9. The rigid bodies served as the local coordinate system (LCS) of the segment, and provided information on the position and orientation of the segment as a whole across time. In contrast, the global coordinate system (GCS) was a mapped volume of the three dimensional space in which the LCS moves. Unlike the LCS, the GCS's orientation was fixed in the X, Y, and Z directions, and so provided a reference point from which the LCS's position and orientation were measured. The GCS was defined in this study as having the Y axis facing parallel to the line of progression of the participant, the Z direction as the vertical, and the X direction pointing laterally to the right side of the line of progression. This is shown in Figure 10.

A 3-D model was created using the two 3D Investigator Position Sensors, each equipped with three 2-D cameras, through a method called direct linear transformation (DLT) (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014). This method assumes the measured segments act as solid, invariable entities, which is not reflective of the nature of many body sections. For example, the foot can flex and extend at the midfoot and toes which changes its shape, but this method refers to the whole foot as one rigid section.

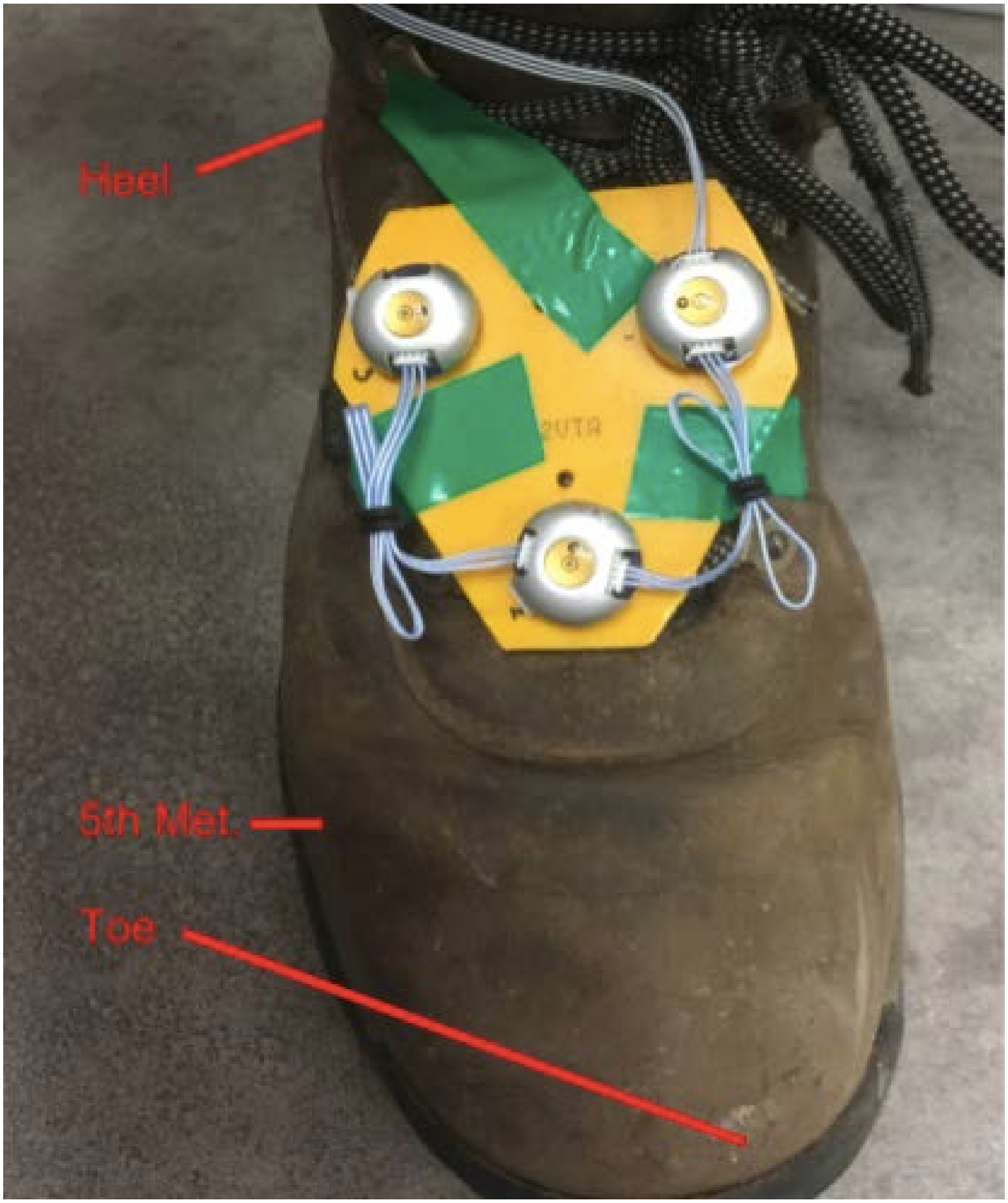

Figure 9. Placement of the rigid body on the upper foot, and the locations of the digitized landmarks of the heel, big toe, and 5th metatarsal.

Figure 10. Global coordinate axes of experimental room.

Protocol

The researcher read the following paragraph to the participant:

"Thank you for coming. As you are already aware, this study aims to analyze fencing footwork to find the differences between how fencers stop for various signaling times. You will be wearing a type of motion sensor that will let us record things like angles, velocities, accelerations, and relative position. It is important that you do not block the markers from the view of the cameras positioned in front and beside you during the trial. Before beginning the trials we ask that you practice stepping to the tempo of a metronome we have set to 120 beats per minute. You are to place your feet down in time with each beat, alternating right and left feet for each beat. Therefore, you should complete a full advance every two beats, meaning both feet take a step. Do not rush your steps so that there is a pause between one step and the next. When one foot lands on the floor the other should begin lifting off. Each step should be between 10 and 20 inches, or 25 to 50 cm. You will be doing 30 trials total. To begin a trial you will be positioned on the starting line. You will hear the metronome begin to beat and you will stand still for the first 4 beats, and then begin advancing on the 5th, with the 5th beat corresponding to your first step. At some point while you are stepping the screen in front of you will turn from black to white and display a large printed "STOP" in red letters. Once you see this signal stop advancing as soon as possible. Treat the signal as if someone were attacking you in fencing. Do not stop advancing until you see the signal presented. There may be instances where the "STOP" does not show up. In this case you will be instructed to stop by the researcher. You may now practice with the metronome and the “STOP” screen. We will begin the trials when you feel comfortable with the setup.”

Each participant performed 30 trials comprised of 20 actual trials and 10 catch trials where there was no signal displayed. This ratio was chosen somewhat arbitrarily as there does not appear to be a “best practices” for the ratio of real to catch trials in the literature. Several studies found have used ranges between 10-20% catch trials to 80-90% real trials (Surburg, 1981; Focke, Stockinger, Diepold, Taubert, & Stein, 2013). However, there are also studies that have used a 3:1 catch to real ratio (Oliveira, Silva, Lund, Farina, & Kersting, 2014). We felt that 20% would be too low for the limited number of total trials being performed, and so one third was decided upon. Catch trials were used to determine if the fencers were stopping when they expected the screen to change or if they were truly stopping when they actually saw it change. Stopping prematurely would have provided inaccurate data, as they would not be performing the action the same way or at the same time as if they were reacting to a real stimulus. For real trials, actions were interpreted as anticipatory if they were performed before 160ms after the cue was given, and these trials were not included in the final results. This was consistent with other studies which have looked at reaction time (Balkó, Borysiuk, & Šimonek, 2016). Provided the participant did not stop during the catch trials, the head researcher instructed them to stop once they were almost touching the desk which supported the computed. The 20 real trials were comprised of 5 trials for each of the 4 different phases. The order of the trials were randomized to avoid practice effects and anticipation.

Data Analysis

There were four phases of fencing footwork defined by this study. They were front foot swing (FS), front foot contact (FC), back foot swing (BS), and back foot contact (BC). These phases are shown together in Figure 3. The contact phases were defined as the period of time when both feet were in contact with the ground, and can be distinguished between front and back by the last foot to make contact with the ground. Swing phases were defined as the period of time when one of the two feet were not in contact with the ground, and can be distinguished between front and back by the foot in the air. The front heel contact was considered the starting point for the front contact, which was characterized by the local minimum in the vertical Z axis. The back toe contact was considered the starting point for the back contact, and was also defined by the local minimum in the Z axis. The reason for the difference in characterization is that the heel made contact first on the front step, but the toe made contact first on the back step. The swing phases were defined as the first portion after the local minimum when the marker rose in the vertical Z axis by 3mm or more between two frames. A stop was defined as the maximum point in the forward Y axis which happened in time with a local minimum in the Z axis. Referencing the Y and Z axes together ensured that the participant was in contact with the ground and had completed a proper stop.

The proportion of time occupied by the four phases was assumed to be equal based on pilot data done under the same conditions as the study, and the demands of the study itself. Namely, stepping in time with the metronome and the requirement that the participants maintain even pacing between steps. The pilot experiment was performed with one volunteer fencer from the same club. They were asked to perform their footwork under the same task conditions as the other participants, and their footwork was recorded using a slow motion feature on the researcher's cell phone camera. The head researcher then observed the amount of time the fencer spent in double support and swing phases and concluded they spent about equal time in each phase. Therefore, each phase was assumed to occupy 25% of each complete advance. Since the metronome was set to play at 120 beats per minute, this equated to 2 beat per second, and each beat contained 2 phases of equal duration. As a result, the total time per phase was assumed to be 0.25s. However, the ratio between phases was further tested as a dependent variable to ensure the pilot data reflected accurate values. The stopping cues were set to go off at the start of one of these phases depending on the trial, (i.e. at the same time as a beat, or 0.25s after a beat). This coordination between the metronome and the stopping cue was made through Microsoft PowerPoint by fine tuning the time at which each slide transitioned to the next (Microsoft, 2015b). The audio was embedded in the slides, and the slides changed from black to the "STOP" signal slide at a specified point in time. When the slide changed, the audio continued playing so that the participant did not receive unintended cues from a lack of audio, but instead had to react to the visual perception of the slides changing. The independent and dependent variables are shown in Table 1.

Table 1. Independent and dependent variables

Independent variable:	Cueing time: Broken into 4 options corresponding to footwork phases: Front foot contact, back foot swing, back foot contact, and front foot swing.
Dependent variables:	Cue-Stop Difference (CSD): The duration of time from when the cue is given until the fencer reaches a local maximum in the Y axis, and a local minimum in the Z axis. Last Foot to Step (LFTS): The last foot to initiate a step before footwork stopped. Difference From Expected (DFE): The difference between when the foot was expected to regain contact after commencing a step, compared to the actual time until stop. Swing-Contact Ratios (SCR): 1) The amount of time spent in contact versus swing for each foot individually for a single advance. 2) The duration spent in each of the four phases for a single advance.

The independent variable was the cueing time. The rationale for choosing this as the independent variable was to attempt to quantify whether there were more vulnerable or less vulnerable parts of the fencing footwork cycle, (i.e. whether there were points when fencers stopped an advance more quickly or more slowly after being given a cue).

The dependent variables were the Cue-Stop Difference (CSD), the Last Foot to Step (LFTS), the Difference From Expected (DFE), and the Swing-Contact Ratio (SCR).

The primary dependent variable was the CSD, which signified the time from the cue presentation until the participant reached a stop.

The CSD was calculated by using a combination of Y and Z axis values for the heel and the big toe of both feet. To identify contact for the front foot, the minimum point for a given step in the Z direction of the front heel was identified, and this was corroborated with the Y axis to ensure the Y was reaching a stop at the same time, or within 5 frames (0.05s) of the Z value. The front swing was defined as the point where the entire foot left the ground. This differed between individuals, by whether they lifted their heel or toe first, but the cutoff was determined to be when there was an increase of 3mm between two consecutive frames in the Z direction. This range was selected with gained experience from data analysis. It was found that the values could fluctuate up to 2mm in static positions, and so a cutoff outside this range was necessary to avoid mistakenly identifying inherent "noise" as critical points. The back contact was also variable, but typically participants would contact with their toe before their heel. Therefore, a similar approach as the front foot was taken with the back toe, (i.e. the lowest point in the Z direction for a given step). The back foot swing was done the same as the front swing but using the back toe as the reference. The CSD was the main parameter used to define the proficiency of the movement, as shorter times were considered the main factor in being prepared to react to an incoming attack.

The LFTS refers to which foot was the last to initiate a step before footwork was stopped. This is presented as either the FRONT or BACK foot. The measure by which a step was defined was any movement of more than 10mm in the Y direction within the time frame of 30ms. This included the completion of the current step if the cue was given in a swing phase. The median foot for each phase was taken as the final value for the LFTS. The LFTS is seen as contributing to the performance of the movement in that it greatly influences the CSD.

The DFE was defined as the difference between when a foot contact would have been expected to happen, compared to the true time it happened. The expected time was determined by multiplying the number of steps taken until the participant stopped by 0.50s, and then adding this time to the time when the first contact occurred. This number was used as the reference point from which the actual time was subtracted. For example, if the participant was cued to stop on the second front swing, they would likely take 4 steps: the first front, the first back, the second front, and a second back. If they had taken 4 steps, and their first front contact happened at 3.50s, this would give an expected contact of 4(0.50s) + 3.50s = 5.50s. If the participant stopped at 5.20s, the DFE would be 5.50s - 5.20s = 0.30s. This metric was intended to evaluate whether and by how much the participants were stopping early in response to the cue, or whether they were letting the steps play out at the expected times despite having seen the cue. Having a consistently negligible DFE would indicate that the participants attributed no urgency to their stop, meaning the cue was not being treated as if it were an attack. If this were the case, it would detract from the applicability of the results.

The SCR was made of two separate but interconnected values: 1) The relative amount of time spent in contact versus swing for a particular foot in a single advance; and 2) The relative amount of time spent in each of the four phases of footwork: FC, BS, BC, and FS. The transition from contact to swing was defined as the first frame after a local minimum where the difference between one frame and the last was ≥3mm in the Z direction. Whether the toe or the heel left the ground last was dependent on the participant, so the last to leave the ground was used in this measure. The transition from swing to contact was defined by the local minimum value in the Z direction of the first part of the foot that reached a local minimum. The front foot more often showed the heel as the first portion of the foot to reach a minimum, whereas the back foot typically showed the toe as the first to reach a minimum. These points were only recorded on non-cued steps to ensure that cueing had no influence on the SCR. Data taken from all possible trials were averaged to create the SCRs. The phases were assumed to each contribute 25% to the total duration of an advance based on pilot data, but this was tested in the experiment to ensure accurate values.

The way to determine from the data when the cue was given was to reference the first foot contact as the 0.0 seconds mark and reference the duration until the cue was activated on the slideshow from that point. The assumption was that the participants landed their first step at the appropriate time, which simply emphasizes the importance of practicing before doing the trials. The audio was configured so the first beat began at the same moment as the timer on the slide began. The fifth beat was programmed to happen at exactly 2.4s, meaning that every front contact cue happened on a second ending in 0.4 (2.4, 3.4, etc). A similar line of reasoning was applied to the other phases. Back contact is 0.5 seconds later, so those cues ended in 0.9, back swing happened at 0.65s, and front swing was 0.15s. The data was recorded with the Northern Digital Inc. (NDI) First Principles program and Microsoft Excel in conjunction with the NDI Optotrak motion capture system (Northern Digital Inc, 2013; Microsoft, 2015). There were no statistical analyses beyond calculating the averages of the CSD, the DFE, and the SCR, and the median of the LFTS.

RESULTS

Trial inclusion criteria

Of the 80 potential trials which could be included, 37 showed complete enough data to reasonably ascertain where critical values were. However, several of them still required interpretation, because one or more critical values (such as foot contact or the beginning of swing) were missing by 10 frames of fewer. To this end, we have decided to group the data into two groups. The first group, called the FULL group, is comprised of all 37 trials where data was reasonably obtained through either interpretation or direct observation. The second group, called the OVERT group, is made of only those trials where interpretation was not required because direct observation was possible. The OVERT group included 26 trials.

Outcomes of CSD

The results for the CSD and a comparison to the original hypothesis are shown in Figure 11. The back swing phase had the lowest CSD of all the phases with 249ms for OVERT and 263ms for FULL. The front swing had the highest CSD out of the four phases with 430ms for OVERT, and 445ms for FULL. This was followed by front contact at 418ms OVERT and 425ms FULL, then back contact at 368ms and 372ms for OVERT and FULL respectively. The FULL and OVERT data sets show a high degree of similarity, but consistently higher values for the FULL data set. A summary of these values is shown in Table 2.

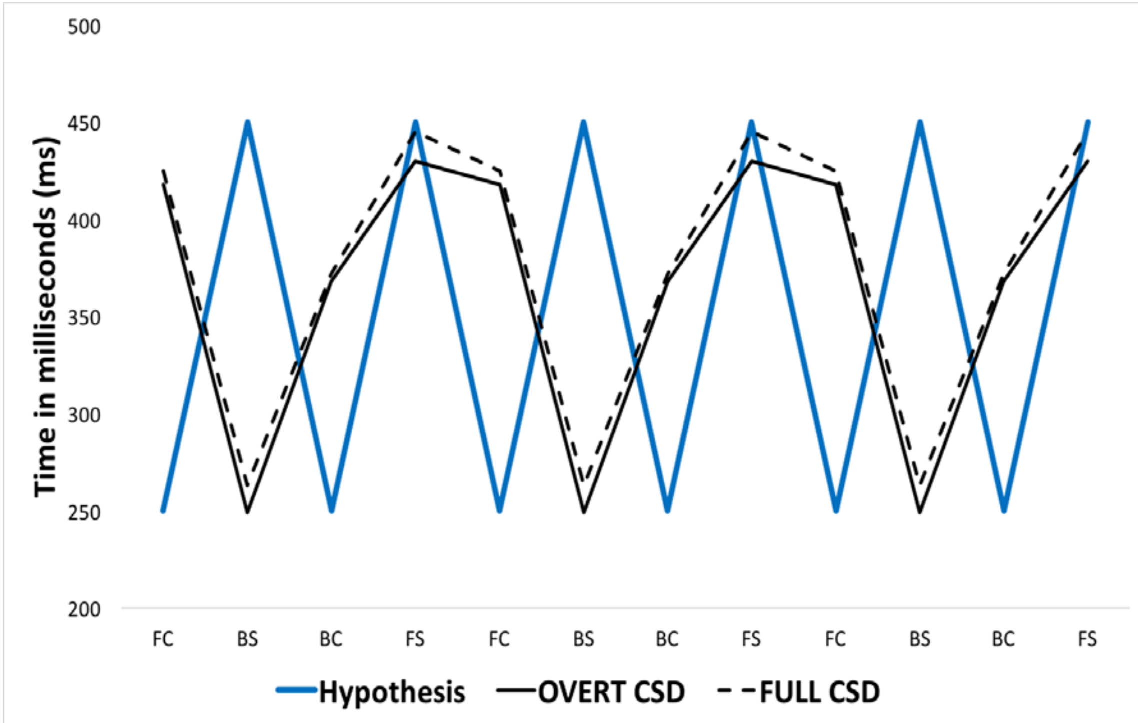

Figure 11. OVERT and FULL CSD compared to hypothesis for each phase across time (ms) over three advances.

Table 2. The number of trials included in data analysis by phase in FULL and OVERT data sets, as well as CSD averages in thousandths of a second (ms).

Cue Phases	Overt Total: 26 (ms)	Full Total: 37 (ms)
FC	(6), +418	(10), +425
BS	(7), +249	(10), +263
BC	(6), +368	(7), +372
FS	(7), +430	(10), +445

Outcomes of DFE

Figure 12. shows the results of the DFEs for each of the four phases. The largest DFE was in the front swing at 289ms and 284ms for the OVERT and FULL data sets respectively. The lowest DFE was in the back swing at 73ms and 42ms for OVERT and FULL. The back contact had a DFE of 132ms and 130ms, and the front contact had a DFE of 82ms and 85ms for OVERT and FULL respectively. These values are shown in Table 3.

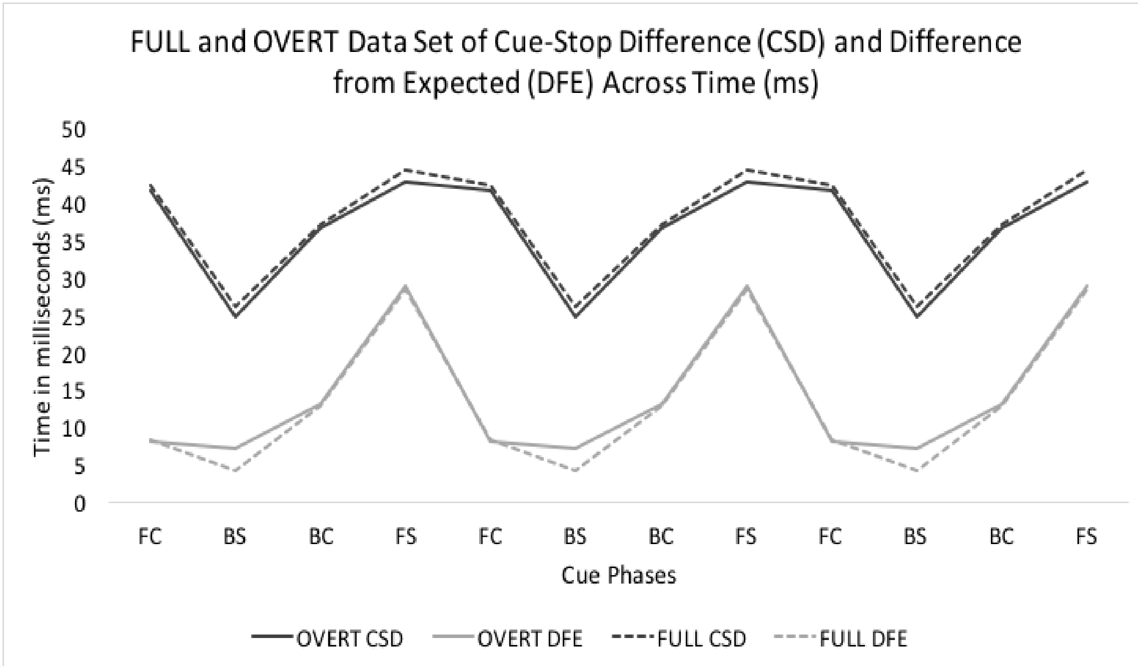

Figure 12. Difference from Expected (DFE) in milliseconds (ms) versus cue phase over three advances.

Table 3. DFE averages in thousandths of a second (ms) for each cue phase.

Cue Phase	Overt Total (ms)	Full Total (ms)
FC	-82	-85
BS	-73	-42
BC	-132	-130
FS	-289	-284

Outcomes of LFTS

The median values for LFTS for each phase are presented in Table 4.

Table 4. OVERT and FULL data set median results for LFTS for each cue phase.

Cue Phase	Overt Data Set	Full Data Set
FC	Back	Back
BS	Back	Back
BC	Front	Front
FS	Back	Back

Of all the phases in Table 4., only back swing showed no additional step before stopping when presented with a cue, which caused it to stop on the same foot which was moving at the time of the cue. All other phases stopped on the opposite foot to the one moving during the cue.

Outcomes of SCR

Figure 13 provides the dual insight of the single foot swing-contact ratios, as well as the timings when the phases happened. This is possible because one step took, in theory, 1.0 seconds. Therefore, it was possible to provide the ratios and phases in terms of percentages as well as in milliseconds simultaneously with the same value by moving the decimal one space to the left. The front and back steps show slightly different SCRs. The front foot had a contact time of 654ms on average, and a corresponding swing time of 346ms. Back step values were 676ms and 324ms for contact and swing respectively. The FC phase lasted 176ms, the BS was 324ms, the BC was 154ms, and the FS was 346ms. It is important to distinguish between the terms contact and swing when referring to each foot individually, and the four phases of FC, BS, BC, and FS when referring to the relationship between the positions of the feet together. These results are summarized in Table 5. and Table 6.

Table 5. Duration of contact and swing for back and front feet individually for a single advance.

Foot	Contact (ms)	Swing (ms)
Front	654	346
Back	676	324

Table 6. Duration of phases of footwork for a single advance.

Cue Phase	Duration (ms)
FC	176
BS	324
BC	154
FS	346

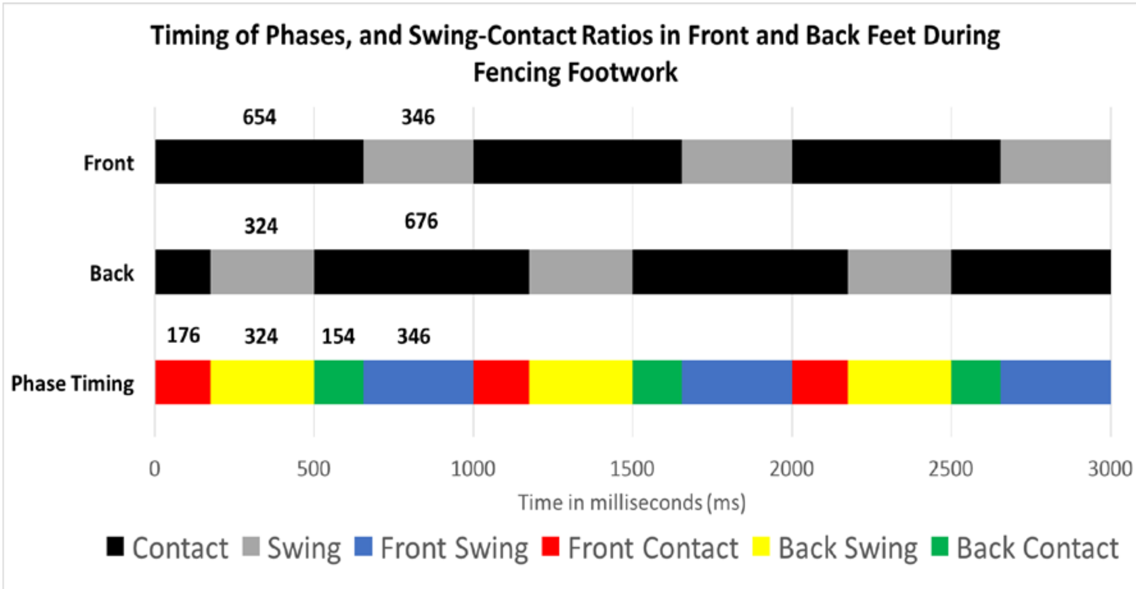

Figure 13. Front and Back Foot Swing-Contact Ratios with Relative Timings in milliseconds (ms) over three advances.

DISCUSSION

This study examined differences in the stopping ability of fencers when they were presented with a visual cue at four different points of their footwork cycle. Stopping ability was assumed to be a core skill of a fencer, in that it positions fencers for optimal attack interception and for other action preparations. The major findings were the order of the phases in terms of participants' delays in stopping after cue presentation as represented by the Cue-Stop Difference (CSD). As well, important findings regarding the contributions of foot placement patterns to the differences in delay length, as described by the Difference from Expected (DFE), the Last Foot to Step (LFTS), and the Swing-Contact Ratios (SCR) were found. Together, these metrics present a unified narrative of the differences in stopping behaviour.

Figure 11 displays the CSD of each phase and shows that the front swing cued trials were the slowest to reach a stop, while the back swing cued trials were the fastest. This contrasts the original hypothesis which stated that both contact phases would be faster to stop than the swing phases. The rationale for the hypothesis was that fencers would use their current contact with the ground in order to begin stopping earlier than swing phases, which first had to regain contact with the ground before applying stopping forces. This was discovered not to be the case, and the reason can be understood with the results of the following three metrics.

Figure 14 shows that the DFE and CSD follow each other closely. The highest and lowest values are the front swing and back swing respectively. The only difference in order is the contact phases are reversed so that the back contact value is higher than the front contact value. Higher values correspond to earlier stopping compared to the expected values for regaining contact. Paradoxically, this would appear to indicate that the fastest phase to stop was the least early to stop, and the slowest phase to stop was the earliest to stop according to expected contact times. However, paring this information with the LFTS and the SCR provides a reasonable explanation for this result. As shown in Table 4. there was only one phase where the front foot was the last to step, the back contact cue, and the other three phases showed the back foot was the last to step. It would be expected that there would be two of each, but this was not the case. Instead of using their initial contact with the ground to begin stopping earlier, the fencers reacting to the contact phase cues took longer to react than anticipated and began their next step, where they would finally stop. This is indicated by the fact that both contact cues resulted in the opposite foot being the last one to step in Table 4, and that contact phase DFEs were around 0.08s and 0.13s in Table 3 for front contact and back contact respectively. This means the additional step was around three quarters of the way complete before the fencers arrived at a stop. Logically, taking an extra step makes sense, given a minimum reaction time of 0.16s as per the study done by Balkó, Borysiuk, and Šimonek (2016). This added time would translate to the fencer beginning their following step before being able to initiate their stopping action. Essentially, the hypothesis underestimated the reaction time of the participant.

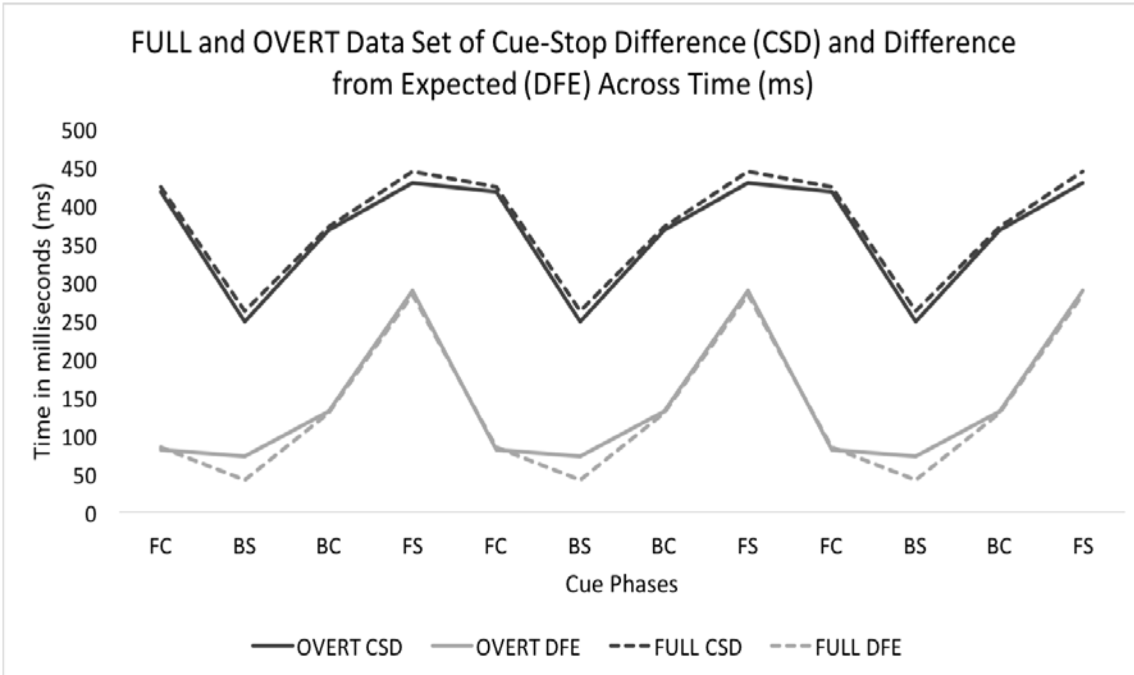

Figure 14. Comparison of CSD and DFE in relation to cue phase over three advances.

The CSD for the contact phases were approximately 0.37s and 0.42s for the back and front respectively, and assuming a minimum reaction time of 0.16s, this would translate to maximum movement times of 0.21s and 0.26s. This represents the time they spent actively trying to stop their step, which only resulted in a 0.08-0.13s gain on when they would have made contact anyway. This suggests that it was quite difficult to overcome the initiated motor program. This finding is similar to Brevers et al. (2018) who looked at proactive and reactive motor inhibition in elite athletes and non-athletes. They used a classification task where participants had to discriminate between right and left pointing arrows using the right and left keys on a keyboard. They were presented with an audio tone that indicated they had to stop classifying as quickly as they could. They found that non-athletes typically reacted 205ms after signal presentation, while athletes reacted 174ms after signal presentation (Brevers, et al., 2018). Since our sample is novice fencers, it would make sense that their reactions would be more similar to the non-athlete population than the elite athlete population. As well, the nature of our task is more physically demanding than inhibiting key tapping, so it would be expected to take longer. Taken together, the reactions observed in our study fall in line with expected values from other studies.

This information does not explain the conflicting implications of the results of the CSD and DFE in the swing phases. The discrepancy is the DFE showed the FS had the earliest stop compared to the expected stop, and the BS had the least early stop compared to expectations, while the CSD showed the FS took the longest to stop, and the BS stopped most quickly. Critically, the swing phases both showed the back foot moving last in the LFTS. This indicates that the front swing took an additional step, just like the contact phases, while the back swing took no additional step. Because the front swing cue resulted in an extra step, it reasonably had a longer CSD. However, because participants were cued at least 0.25s before taking that additional step, compared to the contact phases where that difference was assumed to be approximately 0.0s, they were able to stop their last step much earlier than the contact phase cued trials, resulting in a high DFE. Conversely, the back swing did not take an additional step, which resulted in a lower CSD. Although, having been cued only 0.25s before back contact, the participants were not able to stop much earlier than the expected contact time. In fact the difference was only 0.042-0.073s, which is arguably negligible. This explains the difference in DFE, but it does not ultimately explain why the front swing cued trials show the participants taking an additional step and the back swing cued trials do not.

The SCR was observed to attempt to understand the difference in stepping behaviour between the front and back swings. If there were differences between the ratios of the front and back feet or between the four phase durations, this may give indication about why the front swing cued trials typically resulted in the fencers taking an extra step and why the back swing trials did not. However, Figure 13 shows no apparent differences between the ratios of the front and back feet. Despite this, it does reveal a flaw in the assumptions of the study. Specifically, the protocol was designed with the assumption that participants would spend approximately equal time in each of the four phases, as suggested by pilot data. This is in stark contrast to the values found in Figure 13, where contact phases were found to last about half as long as swing phases.

The swing phases lasted on average 0.335s each or 0.670s total, and the contact phases lasted on average 0.165s each, or 0.330s total. Because the entire step was completed in 1 second, this also represents their relative times: 67% swing, and 33% contact. Comparatively, typical gait patterns in healthy young adults average 22.8% double support (which was how contact phases were defined) (Malatesta, Canepa, Menendez Fernandez, & Canepa, 2017). The difference between expected and tested values suggests that the swing phases started earlier and lasted longer than expected. This gives further support to why the contact phases took an extra step because swing phases were entered after only about 0.16s after the cue was given. Coincidently, this is the exact same amount of time Balkó, Borysiuk, and Šimonek (2016) give for reaction time, meaning it would be impossible for the fencers not to take an extra step in contact phases unless they were anticipating the cue. For the swing phases, this meant that the cue was not given at the start of the phase, but instead approximately 0.10s, or around ⅓, into the phase. It is unknown to what degree this miscalculation influenced the results of the study. Similarly, despite the two swing phases lasting for nearly the same amount of time, 0.346s for front swing, and 0.324s for back swing, the small difference ought not to be overlooked, principally because these numbers are the only quantified difference between the front and back foot swing phases. Meaning, there is currently no other variable to account for the differences in stopping patterns between the front and back swing phases.

Study Significance

The purpose of this study was to describe stopping behaviour in fencers, which has been previously overlooked. This study offers preliminary evidence that footwork phase at time of cue plays a role in the stopping behaviour of fencers. Specifically, this study has found that fencers take the most amount of time to stop when a cue is presented during the front swing phase of footwork. In contrast, fencers were able to stop most quickly when presented with a cue during their back swing. Fencers were found to stop moderately well when cues were presented in both the front and back contact phases. These trends seem to be explained by whether or not an additional step was taken after the cue. All phases resulted in the fencer taking an additional step, with the exception of back swing. It was also interesting that fencers spent about twice as long in swing phases as they did in contact phases. This means they spend a longer duration in single support than in double support, but current research suggests that the type of support fencers occupied during the cue was not the main factor in determining their ability to stop quickly.

Despite these trends, the current data cannot be said to be significant. However, this study may lead to future research, and help focus attention on new lines of questioning about fencing footwork behaviour. The practical applications of this research are potentially twofold. First, the defender may be able to alter the time they spend in a certain phase by changing the size of their steps or their speed, with the goal of spending a greater period of time in more favourable positions. This could manifest as a fencer taking smaller steps to minimize the time they spend in front swing, or spacing the time between their steps out further to increase the duration of double support. Second, a fencer could time their attack to begin at the moment when the defender is most vulnerable. According to current evidence it would be best for a fencer to attack during the opponent's front swing. However, whether or not an attack would be reacted to the same as the visual cue in this experiment is not known, and this point will be discussed in the limitations.

Limitations

Sample Size

The sample size of four fencers is quite low, but not uncommon with pilot research. As well, studies on fencing very often have between 5 and 20 fencers (Zhao, & Fei, 2017; Yanfei, Li, Nana, Lingli, & Warburton, 2018). Regardless of how typical low numbers for participants may be, the fewer participants there are, the less generalizable the data is to the target population. This study tested fencers over 20 trials with real cues, in an attempt to overcome the low sample size, but this too was not without its limitations. The main issue is that these 20 trials were divided among 4 different conditions corresponding to the phases in which they were cued. This reduced each phase's data set to only a handful of trials. Another strategy employed to compensate for the low number of trials was classifying the useable data into two groups: the OVERT data set and the FULL data set. The OVERT data set included all trials with clearly visible critical points. The number of trials in the OVERT data set was 26. The FULL data set included the OVERT data, as well as trials that were missing critical points by no more than 10 frames, or 0.10s. There were 37 trials in the FULL data set. This division allowed for the OVERT data to maintain its superior accuracy, while supplementing it with greater numbers, although less precise, with the FULL data set. While the FULL and OVERT data sets showed a close resemblance, they were not without differences. In future studies, it is recommended that a minimum of 10 fencers be included, with a trial base of at least 50 per condition.

Sensory Fidelity

Fidelity is generally defined as faithfulness, loyalty, accuracy, and exact correspondence to the original (*Oxford Encyclopedic English Dictionary*, 1996). In our current context, sensory fidelity refers to be likeness between the sensory stimuli presented in the original event (fencing) and the experimental setup. Here, two types of fidelity are considered: visual fidelity, and auditory fidelity. Visual fidelity in this study refers specifically to the computer screen as the cue to stop. This is evidently not a representative cue for fencing. A meta-analysis done by Mann et al. (2007) found that increased fidelity has been associated with greater differences in the performance of novices versus that of experts (Mann et al., 2007). This seems to indicate that visual fidelity is important for displaying true, representative reactions. Since this study, and subsequent ones like it, aim to find applicable results, it is highly suggested that future studies employ a more representative cue. This could be achieved either by using another fencer, or if this poses challenges, a video of a fencer performing an attack. Auditory fidelity in this case alludes to the sound of the metronome playing. This added sound would not be present during an actual match, and in fact does not even serve as a substitute for something else, unlike the visual cue. Therefore, the attentional resources that the metronome draws would otherwise be free to be used on performing actions. Future studies should avoid any unnecessary sensory input, auditory or otherwise, to attempt to replicate a fencing match with the utmost fidelity.

Researcher Selected Tempo

In order to accurately time the presentation of cues, this study selected a consistent tempo of 120 bpm to which the fencer had to step. In favouring the accuracy of cue presentation, the fencer were required to step at a pace that may have been unnatural for them. Testimony from a coach at the UPEI Fencing Club indicated that fencers typically perform their footwork at a preferred tempo and pace (Zimmermann, 2018). Changing this tempo to match the requirements of the study may impair a fencer's ability to react to a cue. It may be the case that the imposed tempo demanded increased attentional resources due to its novelty, similar to the sound of the metronome, and would therefore decrease the attentional resources spent on performing the action. Beyond their potential unfamiliarity with the tempo, simply having fencers know that they have to keep to a certain tempo would likely lead to the fencers paying added attention internally to their steps instead of focusing on perceiving and reacting to the cue. Future studies should find a way to present cues accurately while allowing fencers to use self-selected tempos.

Restricted Action Choice

This study was only interested how quickly fencers could stop when presented with a visual cue. While stopping is a common and representative task in fencing, limiting fencers to a single action may not lead to widespread applicability in the greater context of the sport. For instance, if a fencer typically jumps back when presented with an attack, it is quite likely that this motor program will be better established than stopping. The introduction of this study stated that stopping was a reasonable middle ground for stepping back, but this was purely biomechanical and does not account for the internal processes that influence movement behaviour. Future studies ought to include a greater diversity of action choices in order to both compare the performance of different actions, and to allow fencers to select the most natural response for them.

Lack of Video Capture

It is recommended that future studies include videos synced with the Optotrak motion capture system or other tracking software. The primary reason for videos is to confirm that fencers landed their first front contact at the correct time. Here, the assumption was that fencers made the first contact at the appropriate time, and this was only checked by looking for consistent contact times in subsequent steps. If video, and specifically video with audio included, were used, researchers could more accurately verify that fencers were stepping appropriately. The second reason for the inclusion of videos is to corroborate the contact times in the Z axis so that trials that are missing key points could be amended with fewer assumptions. This would have been extremely useful as there were numerous trials that were missing the point of contact and so they had to either be interpreted or discarded.

Lack of Kinetic Measures

This study only included kinematic metrics. This was due to lack of accessibility to appropriate equipment. While kinematics were suitable for the purposes of this study, the addition of kinetic data could have revealed additional information about why fencers reacted as they did. This could have included using a large force plate or several smaller force plates to measure underfoot pressures, which could then be used to infer the movement of the centre of pressure and ultimately how the fencers were balancing throughout the trials. Unfortunately, the lab setting where this study was conducted did not have a large enough force plate or even multiple force plates available. Kinetic measures would also provide a sense of the magnitude of forces being applied, which has important implications for classifying stopping behaviour. For instance, it was not classified in this study whether or not the fencers were balanced when they stopped. If force plate data were included, and it showed a fencer with a centre of pressure near the front toe when stopping, this would indicate that they only barely stopped themself from taking another step, but at the expense of their balance. If applicability is the main objective, then the fencer should not be considered stopped until they have are appropriately balanced. Therefore, future studies should includ force plate data to measure underfoot pressures, which will allow researchers to better interpret movement patterns.

Single Researcher Bias

This study was completed in its entirety by a single researcher. While best efforts were put forward to remain consistent with classifying data, and running the experiment, there is always the chance that individual biases swayed the results in some way. This is especially true when the experiment includes multiple measures, and even more when those measures are continuous instead of finite. In the case of this study, determining the exact points of swing and contact was difficult for several trials and were therefore subject to interpretation, even when using consistent classification criteria. Future studies should benefit from at least two researchers performing the data collection and analysis in conjunction with one another to avoid researcher bias.

Manual Classification

All the data was classified manually in this study. This relates to the previous point of researcher bias, which could have been reduced if a computer program had been used to identify key points. The main reason for the absence of a computer program was the lack of time and experience on the part of the researcher. Future studies ought to use a program designed to identify key points of movements in order to overcome the subjective interpretations associated with manual classification.

Cueing Modes

Woods, Hernandez, Wagner, and Beilock (2017) demonstrated the influence of cueing modes in their study looking at novice and elite fencers and how well they could predict a fencing action based on visual, auditory, or visual-and-auditory cues. They found that novice athletes performed best with visual cues alone, showing a marked decrease in performance when visual-and-auditory were given, and then worst with auditory alone. Experts did equally well with visual and visual-and-auditory, and worst with auditory alone (Woods, Hernandez, Wagner, & Beilock, 2017). The researchers attributed this effect to experts being better at selectively ignoring irrelevant information, whereas novices could not, and so were essentially overstimulated by the additional information. Because we used a visual stimulus for the cue and an audio stimulus for the timing of the steps, the combined presence of these modes may have been taxing on the fencer's attention, and could have led to slower responses. However, it should not have skewed the results in favour of any of the four phases, as audio was kept consistent through the whole trial. A similar study compared visual and tactile stimuli, where the fencing master either stepped forward, or applied pressure to the fencer's blade, and then had the fencer perform a lunge as fast as they could. They found that the tactile stimuli, the blade contact, resulted in a faster reaction than stepping forward (Boryziuk, 2016). Therefore, it might be of interest to compare the results of our experiment under conditions with tactile stimuli.

Conclusion

This study was successful in piloting a kinematic analysis of phase-specific cued stopping in fencing footwork. The results suggest the ability to stop quickly may be periodic, being optimal during the back swing, and worst during front swing. This is contrary to the hypothesis, which argued that the largest differences would be in comparing contact and swing phases. Instead, the largest differences seem to be between the front and back foot, with both of the front foot phases taking longer to stop than the back foot phases. The reason why the front foot phases were slower is attributed to the presence and duration of an extra step after the cue. The extra step appeared to happen for slightly longer in the front contact phase compared to the back contact, and was present during the front swing but not the back swing. Why these differences occurred is not currently understood.

Future studies ought to try to understand why these differences appear, and what can be done as an intervention to minimize the vulnerable, or slowest, portions of the footwork cycle. To understand why fencers took an extra step during some phases, it is important to find whether there is an exact point in their footwork which determines whether they take an extra step or not. The front step was cued on average 0.096s after starting swing, while the back foot was cued on average 0.074s after starting swing. Taking the average of these values, it is hypothesized that cues given before 0.085s into swing phases will result in the fencer not taking an additional step, while cues given after this point with result in an additional step. This assumes that stepping behaviour would be equal among the front and back feet if cues are given with a high degree of precision. This hypothesis does not account for intrinsic factors of fencing footwork as contributing strongly to stepping behaviour. This being said, determining the contribution of intrinsic factors to footwork is another potential area of study. Specifically, determining whether there are difference in fencers' preference to stop on one foot or the other, whether the distance between the feet plays a role in stopping behaviour, whether the asymmetric position of the feet in the en garde position influences fencers ability to stop on a given foot, and finally how weight transfer during footwork all impact the final movement patterns in stopping. After identifying the factors underpinning stopping behaviour, the following line of studies ought to focus on interventions to maximize fencers' abilities to stop optimally. This could be done by changing step length, stepping speed, or shifting the ratios of contact and swing phases to spend more time in a better position. Ultimately, this study serves to develop new questions rather than provide concrete answers, but answering these questions may one day influence performance in the sport of fencing.

REFERENCES

Agostini, V., Balestra, G., & Knaflitz, M. (2014). Segmentation and Classification of Gait Cycles. *IEEE Transactions On Neural Systems And Rehabilitation Engineering*, *22*(5), 946-952.

Balkó, Š., Borysiuk, Z., & Šimonek, J. (2016). The Influence of Different Performance Level of Fencers on Simple and Choice Reaction Time. / A influência dos diferentes níveis de desempenho dos esgrimistas no tempo de reação simples e de escolha. *Brazilian Journal Of Kineanthropometry & Human Performance, 18(4),* 391-400.

Boryziuk, Z. (2016). Type of perception vs. lunge in fencing technique structure. *Revista De Artes Marciales Asiaticas*, *11*36-37.

Brevers, D., Dubuisson, E., Dejonghe, F., Dutrieux, J., Petieau, M., Cheron, G., & ... Foucart, J. (2018). Proactive and Reactive Motor Inhibition in Top Athletes Versus Nonathletes. *Perceptual & Motor Skills*, *125*(2), 289-312.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience,* (3), 201.

Focke, A., Stockinger, C., Diepold, C., Taubert, M., & Stein, T. (2013). The influence of catch trials on the consolidation of motor memory in force field adaptation tasks. *Frontiers In Psychology*, *4*

Geil, M. D. (2002). The Role of Footwear on Kinematics and Plantar Foot Pressure in Fencing. *Journal Of Applied Biomechanics*, 18(2), 155-162.

Gutiérrez-Cruz, C., Rojas, F. J., & Gutiérrez-Davila, M. (2016). Effect of defence response time during lunge in foil fencing. *Journal Of Sports Sciences*, *34*(7), 651-657.

Gutiérrez-Dávila, M., Rojas, F. J., Antonio, R., & Navarro, E. (2013). Effect of Uncertainty on the Reaction Response in Fencing. *Research Quarterly For Exercise & Sport*, *84*(1), 16-23.

Gutierrez-Davila, M., Rojas, F. J., Gutierrez-Cruz, C., Garcia, C., & Navarro, E. (2016). Time Required to Initiate a Defensive Reaction to Direct and Feint Attacks in Fencing. *Journal Of Applied Biomechanics, 32*(6), 548-552.

Malatesta, D., Canepa, M., Menendez Fernandez, A., & Canepa, M. (2017). The effect of treadmill and overground walking on preferred walking speed and gait kinematics in healthy, physically active older adults. *European Journal Of Applied Physiology*, *117*(9), 1833-1843.

Malawski, F., & Bogdan, K., (2016) Classification of basic footwork in fencing using accelerometer. *Institute of Electrical and Electronics Engineering INC.* 51-55

Mann, D. Y., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-Cognitive Expertise in Sport: A Meta-Analysis. *Journal Of Sport & Exercise Psychology*, *29*(4), 457-478.

Martial Arts Beta. (Poster). (2016). Proper en garde position. [Photograph]. Retrieved from https://martialarts.stackexchange.com/questions/6701/why-do-fencers-point-their-back-foot-to-the-side-in-the-en-garde-position

Microsoft (2015a) *Excel*. Redmond, WA, United States of America. Copy in possession of the author.

Microsoft (2015b) *PowerPoint*. Redmond, WA, United States of America. Copy in possession of the author.

Northern Digital Inc. (2013a). *3D Investigator Position Sensor*. Waterloo, ON, Canada. Copy in possession of the University of Prince Edward Island.

Northern Digital Inc. (2013b). *Optotrak Certus System Control Unit*. Waterloo, ON, Canada. Copy in possession of the University of Prince Edward Island.

Northern Digital Inc. (2013c). *First Principles Motion Capture Software*. Waterloo, ON, Canada. Copy in possession of the University of Prince Edward Island.

Northern Digital Inc. (2013d). *Optotrak Wireless Prober*. Waterloo, ON, Canada. Copy in possession of the University of Prince Edward Island.

Oliveira, A. C., Silva, P. B., Lund, M. E., Farina, D., & Kersting, U. G. (2014). Slipping during side-step cutting: Anticipatory effects and familiarization. *Human Movement Science*, 34128-136.

Oxford encyclopedic English dictionary. (3rd ed.). (1996). New York: Oxford University Press.

Pope Greyhound Fencing Club. (Creator). (2018). *Fencing piste dimensions*. [Digital image]. Retrieved from http://popefencing.org/tournaments-101/your-first-tournament/

Powell, R. B. (2001). Using interactive computer-based training to increase skill levels through the rapid acquisition of experience as measured by decreased recognition and reaction times. *Dissertation Abstracts International Section A*, *62*, 2343.

Robertson, D. G., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. N. (2014). *Research methods in biomechanics* (2nd ed.). Champaign (IL): Human Kinetics.

Roi G, Bianchedi D. The science of fencing. Implications for performance and injury prevention. Sports Med 38: 465–481, 2008.

Schmidt, R. A., & Lee, T. D. (2011). *Motor Control and Learning - A Behavioural Emphasis* (5th ed.). Windsor, ON: Human Kinetics.

Schulz, B. (2017). A new measure of trip risk integrating minimum foot clearance and dynamic stability across the swing phase of gait. *Journal Of Biomechanics, 55*107-112.

Surburg, P. R. (1981). Effects of uncertainties of time and occurrence on reaction time of mentally handicapped students. *Perceptual And Motor Skills, 53(2), 355-360*.

Tasuku, K., Hiromitsu, K., Eijun, N., & Michiko, H. (2007). Effects of aging on gait patterns in the healthy elderly. *Anthropological Science*, (1), 67.

Triolet, C., Benguigui, N., Le Runigo, C., & Williams, A. M. (2013). Quantifying the nature of anticipation in professional tennis. *Journal Of Sports Sciences, 31*(8), 820-830.

Turner, A., Bishop, C., Chavda, S., Edwards, M., Brazier, J., & Kilduff, L. P. (2016). Physical characteristics underpinning lunging and change of direction speed in fencing. *Journal Of Strength And Conditioning Research*, (8), 2235.

Williams, L., & Walmsley, A. (2000). Response timing and muscular coordination in fencing: a comparison of elite and novice fencers. *Journal Of Science & Medicine In Sport*, *3*(4), 460-475.

Wifall, T., Hazeltine, E., & Toby Mordkoff, J. (2016). The roles of stimulus and response uncertainty in forced-choice performance: an amendment to Hick/Hyman Law. *Psychological Research*, *80*(4), 555-565.

Woods, E. A., Hernandez, A. E., Wagner, V. E., & Beilock, S. L. (2014). Expert athletes activate somatosensory and motor planning regions of the brain when passively listening to familiar sports sounds. *Brain And Cognition*, *87*122-133.

Xanin Tech. (2014). *Pro Metronome - Tempo, Beat, Subdivision, Polyrhythm*. Copy in possession of the author.

Yanfei, G., Li, G., Nana, W., Lingli, Z., & Warburton, D. R. (2018). Biomechanical insights into the determinants of speed in the fencing lunge. *European Journal Of Sport Science*, *18*(2), 201-208.

Zhao, C., & Fei, Z. (2017). Biomechanical analysis of knee joint mechanism of the national women's epee fencing lunge movement. *Biomedical Research (0970-938X)*, *28*S104-S110.

Zimmermann, L. (2018). Personal interview.

APPENDIX

A)

B)

Figure 15. Example of raw data for the front (A) and back (B) feet.