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Article

The effect of joint angle differences on blade velocity in elite and novice saber fencers: A kinematic study

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SUMMARY

After many years of training, elite saber fencers exhibit extremely rapid blade velocity. However, no prior kinematic research has explained how fencers achieve this. In this work, we measure the influence of arm kinematics on blade velocity in both elite and novice saber fencers. We hypothesized that elite fencers would exhibit smaller elbow joint angle and wrist angle changes, both indicative of blade thrust optimization. Furthermore, we predicted that these kinematic variables would correlate positively with peak blade tip velocity. Three novice and three elite saber fencers of two and six years of experience, respectively, performed a standard vertical saber cut, which we captured on high frame rate video. We discovered a significant difference between the novice and elite elbow joint angle at initiation, the angle at termination, and the angle change. The elbow joint angle change exhibited a strong negative correlation with the peak blade tip velocity (r = -0.83). We determined that angular differences in the wrist were non-significant. Our results suggest that coaches should place greater importance on optimizing elbow joint angles earlier in training. Based on the elite fencer performance, our evidence suggests that the optimal elbow joint angle at initiation for saber fencers may be 110°.

INTRODUCTION

The sport of fencing consists of three weapon categories: foil, epee, and saber. During a fencing bout (a type of sparring match), foil fencers may use the tip of their blade to score a point by jabbing their opponent's torso. Similarly, epee fencers may use the tip of their blade to poke their opponent, but they may attack anywhere on the body. By contrast, saber fencers use any part of the blade to hit their opponents with a cut or thrust above the waist (1). This study focuses on saber, the weapon used by the researcher.

Saber fencing occurs at an extremely fast pace and requires both physical and mental agility to succeed (2). Fencers must coordinate lower and upper limb movement to perform explosive actions, all while in an *en-garde* position. *En-garde* position entails having one foot facing the opponent, and the other foot placed perpendicular, behind the front foot in an L shape (3). While in *en-garde* position, a fencer holds the weapon in their dominant hand away from their body, while their nondominant hand remains at their side. In a bout, saber fencers may perform a variety of actions, including advances and retreats (stepping forward and backward while in *en-garde* position), blade thrusts (moving the blade toward the opponent and landing a hit), and lunges (a full body movement in which a fencer uses their back leg to propel their front leg forward while performing a blade thrust) (4).

While lunges and lower body movement have often been studied in the literature, overall, there is a lack of research on the kinematics of arm movement in saber fencing. A meta-analysis of 37 peer-reviewed fencing studies revealed that lower body movement, specifically the lunge, and foil blade thrusts have been the "principal movement evaluated" (3). While research has been conducted on the fencing foil flick and saber fencing lunge, no studies have been conducted on bladework in saber fencing (5). Apart from research that examined injuries in the arm due to time loss or broken blades, no prior saber fencing research, to our knowledge, examined the kinematics of arm movement (6, 7). Prior research examined the correlation between kinematic variables and attack success, and other research separated elite and novice fencers to measure differences in velocity; however, this research is the first to combine both types of analysis for saber fencing (8-10). This research examined the blade thrust (an arm movement), specifically the vertical blade thrust, without the corresponding lunge (which involves full body movement including the legs).

We hypothesized that the elite fencers would exhibit smaller elbow joint angle change (ΔEJA) and wrist angle change (ΔWA) during the vertical blade thrust to the head, indicators of blade thrust optimization, compared to novice fencers, resulting in a greater peak blade tip velocity.

The key dependent variable was peak blade tip velocity: the faster a fencer strikes, the more likely they are to avoid a parry (block) and reach their opponent before they escape. Thus, blade tip velocity is a strong indicator of attack or scoring success (5). Elbow and wrist angles were the crucial independent variables to consider, as the less time a fencer needs to move their arm, the less energy they expend, and the faster they can recover if they miss the intended target. This research sought to demonstrate the importance of refinement of arm movement in training. While one might think the speed of a moving blade is a product of the wielder's strength, we hypothesized that the kinematics and angular motion of the arm would define the speed and optimization of the blade extension. The literature provided precedent for studying these kinematic variables, including the angle at initiation of the blade thrust, the angle at termination of the blade thrust, and the velocity of different arm regions (10).

Ultimately, we discovered that elbow joint angles (EJAs) at initiation and termination differed significantly between elite and novice groups. After subjecting EJA and peak blade tip velocity to statistical analysis, we found that differences in elbow joint angle values were statistically significant, whereas wrist values were not. Next, we found that elbow joint angle change (the angle at termination minus the angle at initiation) was negatively correlated with peak blade tip velocity (r = -0.83) and positively correlated with total blade thrust time (r = 0.87). This result offered support for the conclusion that elite fencers exhibit more optimized blade thrusts (i.e., fewer degrees of rotation in a shorter length of time), thus achieving greater peak blade tip velocity overall.

RESULTS

We designed an experiment in which three elite and three novice fencers performed a vertical blade thrust within view of our 240 frame per second (FPS) camera **(Table 1)**. We analyzed the elbow joint angles (red) and wrist angles (blue) using the PASCO Capstone angle tool, which allows for 2D angle measurements **(Figure 1A)**. We used different color tracking points to reflect positional measurements of the shoulder, elbow, wrist, and blade tip **(Figure 1B)**. Our model analyzed the entire progression of the blade thrust, from en-garde position (meaning that the fencer is standing in place, ready to strike) to the point of contact with the mask.

Blade Tip Velocity

We first needed to establish the peak blade tip velocity values of each fencer and whether or not a statistically significant difference existed between peak blade tip velocities of elite and novice fencers. We used an auto tracking tool to trace the arm and blade points and an angle tool to measure the angles of the relevant arm arc regions. We found that peak blade tip velocities of the elite group ranged from 17.55 to 19.53 m/s, with standard deviation (SD) = 1.01, whereas those of the novice fencers ranged from 12.97 to 14.93 m/s, with SD = 1.12 **(Figure 2A)**.

We found that the difference in peak blade tip velocity between the novice group and the elite group was statistically significant ($t(4) = 5.52$, $p < 0.05$). These data indicate that elite fencers consistently generate higher blade tip velocities than their novice counterparts.

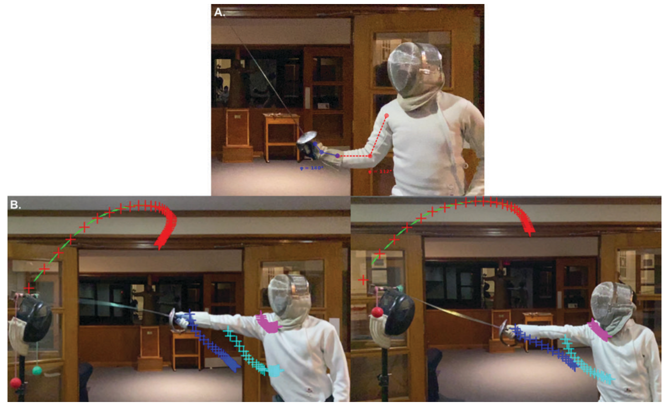

Figure 1: Tracking model. (A) The red angle tool indicates elbow joint angle at initiation, and blue angle tool represents wrist angle at initiation. **(B)** This figure compares the point tracking we performed between an elite fencer (Fencer B; left) and a novice fencer (Fencer F; right). We tracked four points when performing the video analysis for each fencer: blade tip (red), wrist (dark blue), elbow (light blue), and shoulder (pink).

Fencer	Peak Blade Tip Velocity (m/s)	Blade Thrust Time (ms)	EJA Initiation (°)	EJA Termination (°)	Wrist Angle Initiation (°)	Wrist Angle Termination (°)
Elite Fencer A	18.24	196.00	112.05	173.44	140.02	176.88
Elite Fencer B	17.55	300.00	107.98	172.89	135.94	178.47
Elite Fencer C	19.53	199.00	111.21	176.11	145.72	177.03
Novice Fencer D	13.01	336.00	98.32	166.41	117.09	167.56
Novice Fencer E	12.97	367.00	99.59	168.20	134.93	175.85
Novice Fencer F	14.93	299.00	100.25	167.01	133.44	165.32

Table 1: Variable values tested. To find peak blade tip velocity, blade thrust time, EJA at initiation and termination, and wrist angle at initiation and termination. We utilized an auto tracking tool to track each point in motion from initiation to termination of the blade thrust. Angle at initiation was determined by looking at the frame just before the fencer began the vertical blade thrust, and angle at termination was the angle of the fencer's elbow and wrist at the moment of contact with the mask.

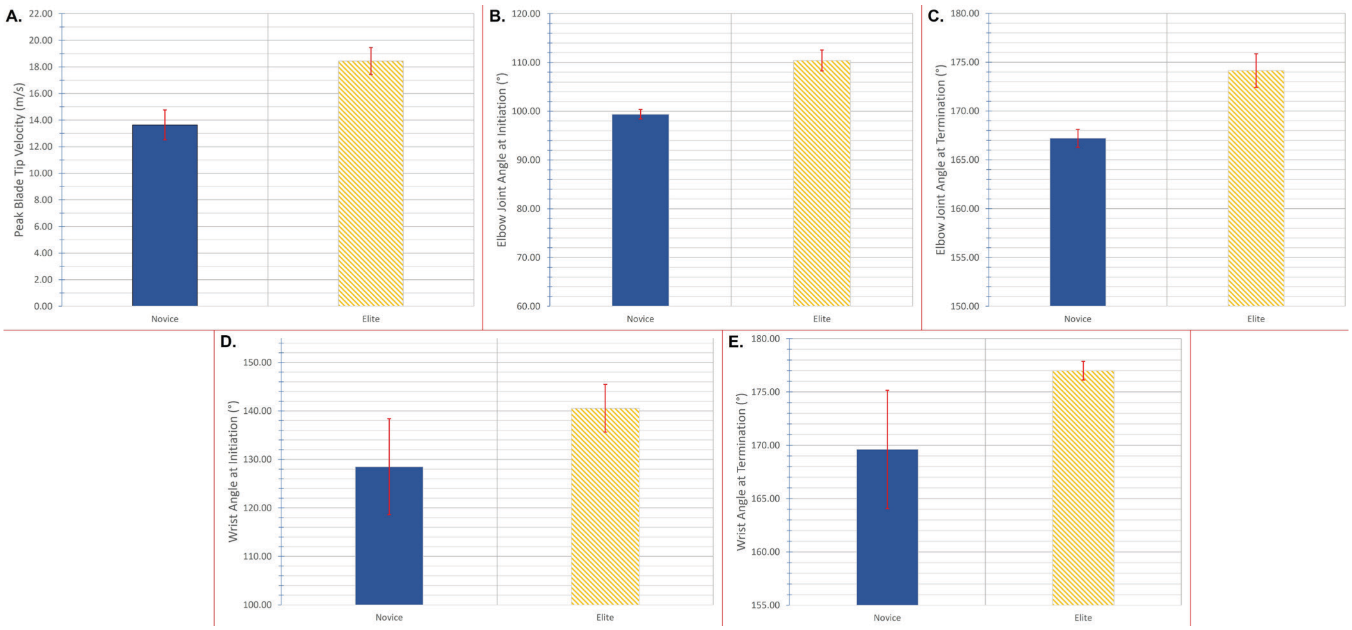

Figure 2: Statistical analysis of velocity and angle measurements for novice and elite groups. Data is shown as mean ± SD for the novice (blue) and elite (yellow) groups. **(A)** Elite fencers returned statistically higher values for peak blade tip velocity than novice fencers (t(4) = 5.52 and $p < 0.05$). **(B)** Elite fencers exhibited statistically more obtuse angle values at initiation of the blade thrust (t(4) = 8.08, $p < 0.05$). At initiation of the blade thrust, we found that elbow joint angle fell within the range of 98.32 ° to 100.25° in the novice group (SD = 0.98), and 107.98° to 112.05° in the elite group (SD = 2.15). This reflected a general trend in which the elite fencers stood in en-garde position with a moderately obtuse EJA_i, whereas the novice fencers stood in only slightly obtuse EJA_i. **(C)** Elite fencers have more obtuse angle values at termination of the blade thrust (t(4)=6.17, $p < 0.05$). Elite fencers at termination of the blade thrust exhibited more obtuse angles (between 172.89° and 176.11°, SD = 1.72) compared to the novice group (between 166.41° and 168.20°, SD = 0.91). **(D)** Wrist angle values at initiation of the blade thrust were non-significant (t(4)=1.16, $p = 0.227$). WA_i values fell between 135.94° and 145.72° in the elite group (SD = 4.91), and between 117.09° and 134.93° in the novice group (SD = 9.90). **(E)** Wrist angle values at termination of the blade thrust were non-significant (t(4)=1.20, $p = 0.221$). WA_t values fell between 176.88° and 178.47° in the elite group (SD = 0.88), and between 165.32° and 175.85° in the novice group (SD = 5.55).

Elbow Joint Angle Kinematics

Next, we sought to understand the kinematics of the arm, which may contribute to the observed greater blade tip velocity for the elite group. The angular kinematic variables we examined included elbow joint angle at initiation (EJA_i), elbow joint angle at termination (EJA_t), and ΔEJA **(Figure 1)**. We found that EJA_i ranged from 98.32° to 100.25° in the novice group (SD = 0.98), and 107.98° to 112.05° in the elite group (SD = 2.15). This reflected a general trend in which the elite fencers stood in "en-garde" position with a moderately obtuse EJA_i, whereas the novice fencers stood in only slightly obtuse EJA_i. Critically, we found that this difference was statistically significant (t(4) = 8.08, $p < 0.05$).

We witnessed a similar trend in EJA_t. We discovered that at termination of the blade thrust, elite fencers exhibited more obtuse angles (between 172.89° and 176.11°, SD = 1.72) compared to the novice group (between 166.41° and 168.20°, SD = 0.91). We found that this result was statistically significant (t(4) = 6.17, $p < 0.05$) **(Figure 2C)**.

To calculate ΔEJA, we subtracted each fencer's angle at initiation from angle at termination ($\Delta EJA = EJA_t - EJA_i$) and found that when comparing ΔEJA between elite and novice groups, this result was statistically significant as well (t(4) = 3.16, $p < 0.05$). With this result, we tested the correlation between ΔEJA with peak blade tip velocity. We discovered that the two variables showed a strong negative correlation: as ΔEJA increased, peak blade tip velocity decreased (r = -0.83) **(Figure 3A)**. In other words, the shorter the distance (as measured by total angular extension), the greater the peak blade tip velocity.

We also found a strong correlation between ΔEJA and total blade thrust time. We found that elite fencer blade thrust time fell within the range of 196 and 300 ms, whereas novice time was longer on average, with blade thrusts ranging between 299 and 367 ms **(Table 1)**. This difference was statistically significant, t(4)=2.35, $p < 0.05$. Moreover, when we tested the correlation between ΔEJA and total blade thrust time for all fencers, we found a very strong positive correlation (r = 0.87). ΔEJA is positively correlated with blade thrust time, suggesting that smaller ΔEJA yields more efficient blade thrusts **(Figure 3B)**.

Wrist Angle Kinematics

Next, we analyzed wrist angle at initiation (WA_i), wrist angle at termination (WA_t), and ΔWA. Unlike the EJA results, we found angles at initiation and termination in the wrist to be non-significant. WA_i values fell between 135.94° and 145.72° in the elite group (SD = 4.91), and between 117.09°

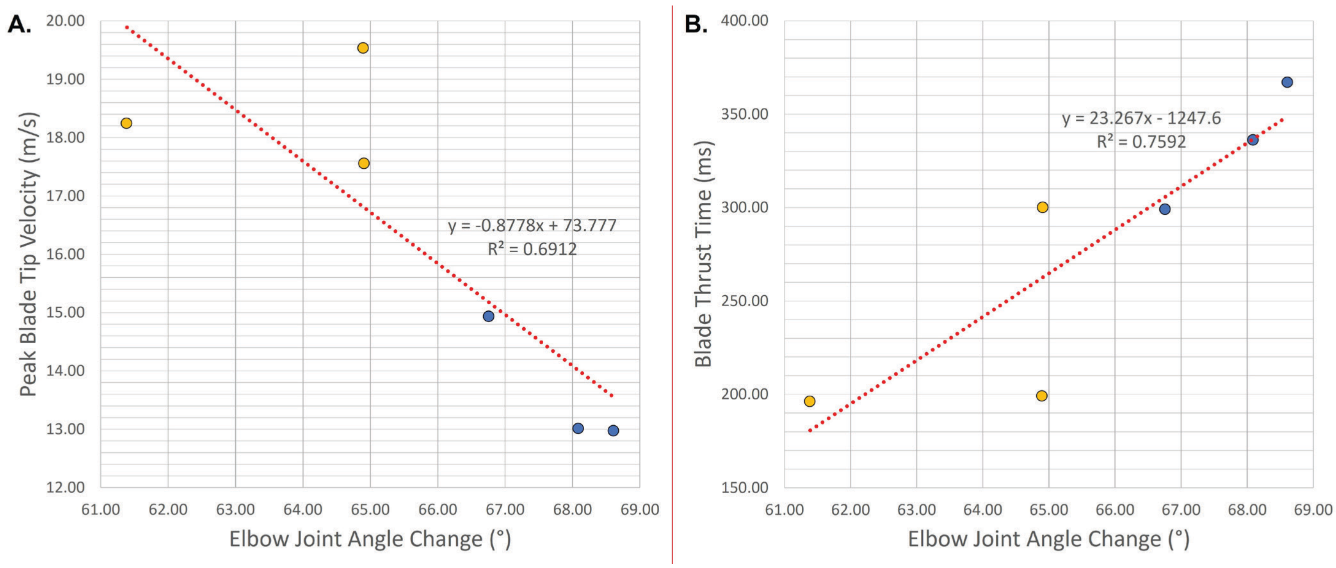

Figure 3: Correlation analysis. (A) Strong negative correlation between ΔEJA and peak blade tip velocity. Novice fencers (blue) exhibited lower peak blade tip velocities as their ΔEJA increased, whereas the reverse was true of elite fencers (yellow). Our Pearson's coefficient indicated an r value of -0.83, and we calculated an R^2 value of 0.69, reflecting a strong correlation. **(B)** Strong positive correlation between EJA and blade thrust time. We found a strong positive correlation between these two variables (r = 0.87; R^2 = 0.76), suggesting that the fewer degrees of angular rotation a fencer performs, the lower the total blade thrust time.

and 134.93° in the novice group (SD = 9.90), with t(4)=1.16, *p* = 0.227 **(Figure 2D)**. We found similar results for angle at termination, with t(4)=1.20, *p* = 0.221. All values for wrist angle at termination fell within the range of 165.32° to 178.47°, with SD = 5.55 for the novice group and SD = 0.88 for the elite group **(Figure 2E)**.

Although we found that angular differences in the wrist at initiation and termination of the blade thrust were non-significant, we discovered an important relationship by qualitatively examining the positional wrist measurements collected in our data that we did not predict in our original hypothesis. Crucially, all three elite fencers raised their hands vertically at the beginning of the action, generating greater vertical distance with which the blade tip could accelerate. In contrast, all members of the novice group initiated the blade action immediately, moving the bell guard directly toward the mask without raising their hands vertically. Whereas novice fencer F's wrist (right; blue marker) exhibits more horizontal trajectory, elite fencer B (left; blue marker) exhibits greater vertical trajectory of the arm throughout the blade action **(Figure 1B)**.

DISCUSSION

Based on the consistency of the elite group's angle at initiation and termination in EJA, we determined that optimal EJA_i for saber fencers may be approximately 110° (slightly more than a right angle), whereas the optimal EJA_t could be approximately 174°, slightly less than straight due to the bell guard extending at a lower height than the mask. Of course, fencers receiving coaching at different fencing clubs would likely return different optimal angles, but it is also likely that other coaches would train their fencers to adopt similar ranges.

As hypothesized, our evidence showed that elite fencers exhibited greater peak blade tip velocity than the novice group. We determined that elite fencers exhibited more obtuse EJA_i and EJA_t than novice fencers, as well as smaller ΔEJA. There are a few possible reasons why the elite fencers exhibited more obtuse joint angles than the novice fencers. First, by beginning in a more obtuse EJA position, fencers need to extend their arms less during an attack. This more obtuse position is also likely advantageous for parries, or blocks, as the farther one's blade is extended, the easier it is to cut off an opponent's angle of attack.

The smaller ΔEJA values for the elite fencers illustrate the extent of their arm optimization: the elite group generated the highest peak blade tip velocities while performing the fewest degrees of rotation. Moreover, since ΔEJA values exhibited a strong correlation with blade thrust time (r = 0.87), ΔEJA seems to be a strong indicator of blade thrust efficiency.

The differences between the elite and novice groups likely rest in the fact that the elite fencers received training for six years, whereas the novices had only trained for two years. Prior research has revealed that training can lead to greater optimization of the blade motion, although research is lacking on the duration of time over which improvement occurs. One study found upon statistical analysis that agility training could improve a fencer's reaction time (11). Thus, future research could examine the length of time it takes for novice fencers to integrate movements and methods taught by their coaches. Moreover, based on the significance of the results, our evidence suggests that beginner fencers may diverge sharply from the experience and understanding of more elite fencers with regard to how to perform a blade thrust. Perhaps coaches can place even greater importance on standardizing elbow joint angles early on, and perfecting blade velocity.

Considering that the wrist plays a critical role in every fencing action, we were surprised to find no significant differences between elite and novice fencer wrist angles. Perhaps the exact initiation and termination angle values of the wrist are non-significant, however, and instead what happens with the wrist *during* the action plays a role. Further research would need to be done with a larger sample size and more complex video imaging to understand this arm motion more fully.

Importantly, our finding of optimal EJA could differ in an actual bouting scenario. In bouting conditions, a fencer must adjust to various factors such as their distance from the opponent and their opponent's height. In this study, we placed the mask at a height of 1.63 meters from the ground, but fencers could be taller or shorter, or closer or farther, likely affecting the angle at termination of the blade thrust. Regardless, our finding is important, as it suggests that greater velocity (indicative of striking power) can be achieved with a more obtuse starting arm angle and with a terminating attack angle at near full extension. With our result in mind, fencers would be sure to maintain a more relaxed, obtuse arm position, instead of hiding the elbow under the shoulder, as was commonplace in the novice fencers.

In our study, human (measurement) error could have affected the results in two major areas. First, since we performed some position tracking manually, point tracing could have been imprecise, resulting in velocity and angle measurements being slightly inaccurate. Second, although the test subjects were instructed to strike the target vertically in proper form as quickly as possible, any of the subjects might not have hit the target with the maximum velocity they were capable of. Moreover, any of the fencers could have had undisclosed ailments or fatigue which could have influenced the results. Regardless, we do not believe this would have materially altered the results of the study, and we were sure to test all fencers within the same period of time (after training and warmup for both groups) to avoid differences in levels of fatigue.

Ideally, we would have had a larger selection of fencers in a smaller age group range, and a more equal distribution of male and female fencers between the elite and novice groups. Future research could expand the scope of this study and assess similar metrics with a larger sample size. Ideally, we would have preferred all elite and novice fencers to be the same age, but it was expected that novice fencers tended to be younger. Regardless, we believed that angular differences would correlate more with experience and training rather than age or strength.

While nominal differences in strength related to secondary sex characteristics could have slightly skewed the novice results, prior research in epee kinematics reveals that upon statistical analysis, there were no significant kinetic differences between men and women performing lunges, an action heavily reliant on strength and speed (10). Further research would need to be performed to determine the extent to which this result would hold with regard to arm movement in saber fencing. For the sake of clarity, we would assume that this unequal representation of males and females could have had some effect on the results.

While we utilized a 240 FPS camera, a camera with more frames per second (i.e., 600+) would have been more accurate. Additionally, more advanced tools for 3D measurement would have been useful (e.g., depth camera, sensors, surface electromyography), as some past studies have used more advanced tracing technology (12). However, other studies have performed 2D measurements (5). For this reason, we felt comfortable with accurate 2D measurements.

While the type of blade used is not necessarily a source of error, some blades are lighter than the one we provided. Research using the same methodology could thus return even higher peak blade tip velocities due to greater flexibility or lighter weight of the blade. Although we used the same blade for each fencer, they were given time to adjust to the blade so that they felt comfortable with it before completing the task posed by the study.

Overall, our data indicate the extent to which elite fencers can optimize their attacks. Beyond generating consistently higher blade tip velocities than their novice counterparts, elite fencers exhibited more obtuse EJA_i and EJA_t than novice fencers, as well as smaller ΔEJA. The smaller ΔEJA values for the elite fencers correlated strongly with blade velocity and blade thrust time: elite fencers reached the highest peak blade tip velocities while performing the fewest degrees of rotation in the shortest period of time. Thus, ΔEJA seems to be a strong indicator of blade thrust efficiency. This finding is relevant both for fencers attempting to find ideal angles suited for attack and for coaches attempting to better train their students. Our results suggest that coaches could place greater importance on optimizing elbow joint angles earlier in training, perhaps tuned to our finding that the optimal elbow joint angle at initiation for saber fencers may be 110°. Future research could utilize our findings to investigate further into the complex interplay of angles and velocities that characterize a blade thrust.

MATERIALS AND METHODS

Participants and Set-up

This research was conducted at a relatively small fencing studio with permission of the head coach and with the informed consent of all participants involved. Permission for ethical experimentation was attained by a Scientific Research Committee.

We assembled a group of novice fencers (two female, one male) and elite fencers (three male) from the local fencing club of one of the researchers. Participants were selected based on years of experience. As a result of the COVID-19 pandemic, we were forced to limit our research to a small sample size. We defined years of experience while considering the number of individuals at the club who could actually meet that criterion. Consequently, of the novice fencers, two had two years of experience and one had just under two years of experience. In the elite group, two had six years of experience, and one had just reached seven years. Notably, these ranges of experience (2 years for novice and 6-7 years for elite) are consistent with the experience levels previously reflected by elite and novice fencers in the literature (8). All fencers had trained at the same fencing studio and worked with the same coaches. Additionally, all three elite fencers had competed at a comparable number of national tournaments, whereas the novice fencers had only competed locally.

Two of the novice fencers were female, and the rest of the fencers were male. Among the novice and elite fencers studied, the participant ages and heights ranged from 13-19 (Novice: 13.95 ± 1.05 years, 158.7 ± 6.3 cm; Elite: 17.5±1.5 years, 182.4±5.4 cm).

At the site where the study was conducted, we constructed a stand and placed a standard electric saber mask on it. Each fencer was instructed to stand in an *en-garde* position and was allowed to adjust to their desired distance from the target; as reflected in the literature, not standardizing the distance from the target is necessary to ensure that each fencer hits the target at whatever angle they usually would in a bout situation (5). The camera was positioned to capture a side-on view of the fencer.

Each participant was instructed to wear an underarm protector, white jacket, electric glove, electric mask, and hold the saber. The saber itself was comprised of a grip, a bell guard (to protect the hand), and an 88 cm blade. The action to be performed was a vertical blade thrust with the saber blade, which was understood to include a few requirements. First, the fencer needed to start in an *en-garde* position, as they would typically stand on a fencing strip in a real bout. The fencer would extend their arm forward until they contacted the mask. Importantly, no instruction was given in terms of how the thrust should be performed other than 'vertically' and 'on the researcher's command'. The purpose of this omission was to ensure that we measured each fencer's individual performance in relation to their experience level, instead of trying to improve their blade thrust during the study. Because sabers made by different manufacturers may have different weights, we controlled for differences by using a standard Absolute Fencing™ blade (359 g total saber weight).

Recording and Video Analysis

Recording was taken with a 240 FPS camera. While higher FPS speeds would have been desirable, especially for measuring blade tip speed while it approached peak velocity, the camera was able to pick up peak blade tip speeds with minimal blurring. After the study was conducted in the fencing studio, each video was uploaded to PASCO Capstone for video analysis. Once imported into Capstone, "Properties" settings were adapted to the 240 FPS camera by setting playback frame rate to 240 FPS to ensure accurate measurements at real-time speed. The frame increment was set to one, and four objects were created to track the blade tip, wrist, elbow, and shoulder, respectively, in each project (one "project" for each fencer on which the video analysis was performed). To ensure distance measurements were accurate, we calibrated measurements using the known length of the saber. After calibration and settings were complete, we used an angle tool to measure each fencer's angle at initiation and angle at termination for both the wrist and elbow **(Figure 1A)**. The angle at initiation was determined by looking at the frame just before the fencer began the vertical blade thrust, and the angle at termination was the angle of the fencer's elbow and wrist at the moment of contact with the mask.

Tracking points, for both the angle tool and for object tracking in PASCO Capstone, were determined in relation to small markers placed on each fencer's outer jacket on each relevant arm zone (shoulder, elbow joint, wrist, and blade tip) **(Figure 1B)**. In Capstone, we utilized an auto-tracking tool to track each point in motion from initiation to termination of the blade thrust. Occasionally, an object tracking marker would not be picked up by the auto tracker, so they were manually tracked in increments of one frame. For velocity measurements, we calculated velocity vectors using composite x- and y-vectors provided by Capstone to account for directional motion. We then calculated the resultant vectors.

Statistical and Correlation Analysis

We performed our statistical and correlation analysis using MATLAB and Microsoft Excel. Comparing our values to a significance level of 0.05 for each intergroup comparison, we chose a one-tailed *t*-test as we had predicted that there would be an increase in a specific direction. Specifically, we predicted that the elite fencers would have more obtuse (greater) angles at initiation, termination, and max blade tip velocity, and more acute angle changes. For the t-tests performed in Excel, we utilized the data analysis feature (specifically, the option for "*t*-test: Two-Sample Assuming Unequal Variances", with an alpha value of 0.05, and four degrees of freedom). For the linear correlation performed in MATLAB, we used the provided "corrcoef" function, which revealed the overall strength of the correlation through a count matrix and confirmed the r value for correlation using the "CORREL" function in Excel. This correlation analysis utilizes the Pearson function.

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