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Kinematic determinants of weapon velocity during the fencing lunge in experienced épée fencers

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The lunge is the most common attack in fencing, however there is currently a paucity of published research investigating the kinematics of this movement. The aim of this study was to investigate if kinematics measured during the épée fencing lunge had a significant effect on sword velocity at touch and whether there were any key movement tactics that produced the maximum velocity. Lower extremity kinematic data were obtained from fourteen right handed club épée fencers using a 3D motion capture system as they completed simulated lunges. A forward stepwise multiple linear regression was performed on the data. The overall regression model yielded an Adj R^2 of 0.74, $p \leq 0.01$. The results show that the rear lower extremity's knee range of motion, peak hip flexion and the fore lower extremity's peak hip flexion all in the sagittal plane were significant predictors of sword velocity. The results indicate that flexion of the rear extremity's knee is an important predictor, suggesting that the fencer sits low in their stance to produce power during the lunge. Furthermore it would appear that the magnitude of peak flexion of the fore extremity's hip was a significant indicator of sword velocity suggesting movement of fore limbs should also be considered in lunge performance.

Key words: *fencing, kinematics, lunge, regression analysis, velocity*

1. Introduction

The lunge is the most frequently used successful attack in fencing. The most effective lunge is produced with explosive power and surprises the opponent to make the pointing movement of the sword known as the touché. The sword arm is extended and then the rear lower extremities are straightened as the front lower extremities kick out, reaching forward. This causes substantial distance to be covered. A perpendicular foot placement with the front foot pointing forward has been identified as the optimum position for peak power and velocity of the body towards the opponent during a fencing lunge [1]. The asymmetry in the lunge movement as it is within most movements in fencing has led researchers to investigate asymmetries in the fencing population with conflicting results reporting anthropometrical asymmetries [2], but none were observed in lower limb kinetics and kinematics [3]. The lunge movement is initiated at the legs through a kinetic chain about the ankle, knee and hip joints, combined with the upper body movements to move the sword as fast as possible towards the opponent in an attempt to achieve touché.

Previous research has provided evidence that the speed of the sword performing the touché is faster in elite fencers compared to novice due to the increased speed of the centre of mass generated from the foot to ground interaction [4]. Further research has identified that strength (relative to body mass)

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and in particular, time to peak force production, measured in the concentric phase, was the best predictor of lunge performance when using a supine squat machine as an indicator [5]. Evidence of other indicators for lunge speed include drop jump height and thigh cross-sectional area [6]. Whilst this research has identified predictors of lunge performance separate from the actual movement itself, for coaching purposes, identifying the actual movement variables that contribute to a high sword velocity may provide an insight into desirable movement strategies.

There appears to be a paucity of published research investigating kinetics and kinematics of the fencing lunge. However, research investigating lunges with different movement strategies in badminton reported a lack of a significant effect of lunge strategy on peak extensor moments of the hip and knee, with only the ankle joint reporting a relatively small effect [7]. Whilst it is clear that increasing the ability of the lower limbs to produce larger forces and at a faster rate should increase the speed of the lunge and subsequently of the touché, it is not clear how much any potential differences in movement strategies of the lower extremities influence the performance of the lunge.

The aim of this study was firstly to investigate if the kinematics measured during fencing lunges of épée fencers had a significant effect on the sword velocity at touché. Secondly, if an effect on performance was identified, what the key movement strategies were that produced the maximum velocity of the sword at touché. Such findings may assist in elite fencers altering their movement strategies during the lunge to enhance performance.

2. Materials and methods

2.1. Participants

Fourteen right handed club level épée fencers (males = 9; females = 5; mean ±SD, age = 26.2 ± 1.3 years; height = 175.7 ± 6.2 cm; mass = 75.6 ± 8.2 kg) with a minimum of 3 years' experience, volunteered to take part in this study. All were free from musculoskeletal pathology at the commencement of data collection and provided written informed consent in accordance with the declaration of Helsinki. Ethical approval for this project was obtained from the School of Psychology ethics committee.

2.2. Procedure

An eight camera motion analysis system (Qualisys^{TM} Medical AB, Gothenburg, Sweden) captured kinematic data at 250 Hz from each participant. Participants performed 5 fencing lunges each with their right leg as their front leg and their left leg as their back leg as they were all right handed. Calibration of the motion analysis system was performed before each data collection session. Only calibrations which produced average residuals of less than 0.85 mm for each camera for a 750.5 mm wand length and points above 4000 were accepted prior to data collection.

The marker set used for the study was based on the CAST technique [8]. Retro-reflective markers were attached to the pelvis, right-thigh, right-shank and right-foot in the following locations: 1st and 5th metatarsal heads, medial and lateral malleoli, calcaneus, medial and lateral epicondyle of the femur, greater trochanter of the right leg, iliac crest, anterior superior iliac spines (ASIS) and posterior superior iliac spines (PSIS). The hip joint centre was defined using the Bell et al. [9] equations via the positions of the ASIS and PSIS markers. Tracking clusters were positioned on the right thigh and shank. Clusters were comprised of four 19 mm spherical reflective markers mounted to a thin sheath of lightweight carbon fiber with a length to width ratio of 1.5–1, in accordance with the Cappozzo et al. [10] recommendations. In order to define the anatomical and technical reference frames of the pelvis, right-thigh, right-shank and right-foot, a static reference trial was captured with each participant in the anatomical position. This allowed the positions of the anatomical markers to be referenced in relation to tracking clusters.

2.3. Data processing

Dynamic movement trials were processed using Qualisys Track Manager in order to label anatomical and tracking markers, following which they were exported as C3D files. Three dimensional (3-D) kinematic parameters were quantified using Visual 3-D (C-Motion Inc., Germantown, USA) and filtered at 12 Hz using a zero-lag low pass Butterworth 4th order filter. This was determined as being the frequency at which 95% of the signal power was contained below. Angles were created using an XYZ sequence of rotations [11] referenced to co-ordinate systems about the proximal end of the segment, where X = sagittal; Y = coronal and Z = transverse plane. Trials were normalized to 100% of the lunge phase then processed gait trials were averaged. 3-D kinematic measures from the hip, knee and ankle which were extracted for statistical analysis were 1) angle at initiation, 2) angle at termination of movement, 3) range of motion, 4) peak angle and 5) relative range of motion from initiation to peak angle, 6) angular velocity at initiation, 7) angular velocity at termination of movement and 8) peak angular velocity.

2.4. Statistical analyses

A multiple regression analysis with sword velocity as criterion and the kinematic parameters as independent variables was conducted using a forward stepwise procedure with significance accepted at the $p \leq 0.05$ level. The independent variables were examined for co-linearity prior to entry into the regression model using a pearsons correlation matrix and those exhibiting high co-linearity $R \geq 0.7$ were removed. The results were analysed using the SPSS for Windows version 20.0 (SPSS, Chicago, IL) software package.

3. Results

The angular kinematic parameters are reported in Tables 1–4. Mean ±SD sword velocity was observed to be 12.8 ± 3.3 m/s. Regression analyses were performed with sword velocity expressed in m/s as the dependent/criterion variable. The overall regression model yielded an Adj R^2 of 0.74, $p \leq 0.01$. The results show that the rear extremity's knee range of motion in the sagittal plane (B = 0.72, t = 4.79), Adj R^2 = 0.36, $p < 0.01$, peak hip flexion of the rear extremity's hip in the sagittal plane (B = 0.49, t = 2.99), Adj R^2 = 0.24, $p < 0.01$ and peak flexion of the fore extremity's hip in the sagittal plane (B = 0.39, t = 2.67), Adj R^2 = 0.14, $p < 0.05$ were significant predictors of sword

Table 1. Lower extremity joint angulation from the right side in the sagittal, coronal and transverse planes

Right side	Hip	Knee	Ankle
Sagittal plane (+ = flexion/ – = extension)			
Angle at initiation (°)	34.8 ± 14.1	49.1 ± 10.3	–69.3 ± 9.7
Angle at termination (°)	101.9 ± 13.0	92.5 ± 8.1	–72.9 ± 8.0
Range of motion (°)	67.1 ± 18.2	43.4 ± 14.5	8.6 ± 6.0
Peak range of motion (°)	67.2 ± 18.2	22.5 ± 16.9	23.9 ± 10.2
Peak angle (°)	10.2.0 ± 13.0	26.6 ± 12.3	–45.5 ± 11.2

Table 2. Lower extremity joint angulation from the left side in the sagittal, coronal and transverse planes

Left side	Hip	Knee	Ankle
Sagittal plane (+ = flexion/ – =extension)			
Angle at initiation (°)	6.4 ±10.3	37.6 ±11.1	–84.9 ±5.8
Angle at termination (°)	–8.6 ±6.7	6.8 ±7.4	–64.0 ±8.9
Range of motion (°)	15.0 ±8.3	30.7 ±10.7	21.4 ±10.1
Peak range of motion (°)	3.3 ±2.8	5.6 ±5.5	27.4 ±14.0
Peak angle (°)	9.7 ±10.9	43.2 ±13.9	–57.6 ±13.4

Table 3. Lower extremity joint angular velocities from the right side in the sagittal, coronal and transverse planes

Right side	Hip	Knee	Ankle
Sagittal plane (+ = flexion/ – = extension)			
Velocity at initiation (°/s)	14.8 ± 8.8	56.0 ± 51.5	1.4 ± 34.9
Velocity at termination (°/s)	18.1 ± 19.7	38.4 ± 43.3	–21.2 ± 26.3
Peak flexion velocity (°/s)	304.3 ± 87.2	391.4 ± 79.2	568.3 ± 240.1
Peak extension velocity (°/s)	–88.0 ± 79.5	370.7 ± 188.9	–235.3 ± 143.3

Table 4. Lower extremity joint angular velocities from the left side in the sagittal, coronal and transverse planes

Left side	Hip	Knee	Ankle
Sagittal plane (+ = flexion/ – = extension)			
Velocity at initiation (°/s)	–5.2 ± 18.1	–0.7 ± 29.3	–2.8 ± 2.0
Velocity at termination (°/s)	–0.5 ± 14.6	–4.9 ± 12.3	5.5 ± 26.8
Peak flexion velocity (°/s)	86.7 ± 36.0	75.8 ± 38.4	219.6 ± 154.9
Peak extension velocity (°/s)	–133.2 ± 61.4	–245.6 ± 108.5	–80.0 ± 61.4

velocity. All other variables were excluded from the analyses as they did not sufficiently contribute to the overall regression model.

4. Discussion

This study aimed to determine the 3-D kinematic elements of the lower extremities that contribute most extensively to weapon velocity during the fencing lunge. This investigation represents the first to examine the biomechanical elements of the fencing lunge pertinent to the development of high weapon velocities.

The results of the current investigation suggest that the peak velocity of the sword during an épée fencing lunge can be strongly predicted from a select number of discrete movement characteristics of the fencer. In particular the rear extremity's knee range of motion and peak flexion of the hip in the sagittal plane, appear to be the best indicators of achievement of a high sword velocity. It seems logical that if there were to be predictive indicators of sword velocity they would come from the rear lower extremities side of the fencers as this is the side that drives the body towards the opponent [12]. According to Cronin et al. [5] when investigating strength measures in relation to the lunge, they found that time to peak concentric force was the most significant predictor of lunge performance. This would further substantiate the notion that the power from the rear lower extremities is a significant determinant of sword velocity as the quicker the time to peak force the more powerful the lunge. This supports the current investigation as knee extension range of movement (ROM) and peak hip flexion would lead to the magnitude and rate of propulsive force development, facilitating the development of weapon velocity from the rear lower extremities. The results from the present study support and expand on those of Gholipour et al. [13] who observed knee flexion in elite fencers is greater at the initial on guard stance compared to novice and that the amount of knee extension in the rear lower extremities during the lunge affects the overall lunge performance. Together these results suggest greater range of motion at the rear lower extremity's knee increases sword velocity. In addition, Gholipour et al. [13] observed hip flexion to be greater at the end of the lunge in the elite fencers compared to the novice fencers, again this supports the findings of the present study which suggests that hip flexion is a predictor of sword velocity. This emphasises the fact that the fore lower extremities should not be overlooked as the results imply that the magnitude of the peak flexion of the hip was also a significant indicator of sword speed. As mentioned previously, the fore lower extremity's foot kicks out during the lunge as the rear lower extremity's are straightening. Peak flexion at the hip demonstrates that there is a greater projection of the front lower extremeties during the lunge which increases the sword velocity. Previous authors investigating the determinants of the lunge through rear lower extremity's foot placement [1] and strength [5] have all focused on the importance of the back leg. The results from this study suggest that whilst a focus on the rear extremity movement strategies of épée fencers may enhance performance, the movement of fore lower extremities should also be considered, a fact that may previously have not been so apparent.

The regression analysis shows that whilst lower extremity kinematics account for a high proportion of variance in sword velocity, there is still variance that could not be accounted for by the 3-D kinematic parameters observed in the current investigation. Whilst this study considered the contribution of the lower extremities to the sword velocity, no inferences were considered with regards to the torso or arms and their influence on resultant sword velocity in fencers. Therefore it is recommended that future research consider the upper body movement kinematics pertinent to the development of sword velocity during épée fencing.

Whilst previous research has identified indicators of lunge performances through strength, jump performance and muscle volume [5], [6], this study provides evidence that the technique of the lower body of the fencer is vital to performance and should therefore be considered in conjunction with indicators which may be enhanced through strength and conditioning. The level of fencers who volunteered in the study were club level fencers. As sword velocity was previously identified in being higher in elite level fencers [4], future research is needed to identify if differences in kinematics and kinetics can identify why this is the case. Such research should consider the findings of this study and investigate differences in the lower extremity movement strategies highlighted as influencing sword velocity.

4.1. Practical applications

From a practical stand point the research implies that to perform optimally the fencer requires a low on guard stance produced through knee flexion to allow the most effective ROM about the joint. This supports coaching literature which always emphasises that fencers should bend their legs as much as they can and sit in their stance [11]. Therefore, strength and conditioning should focus on increasing quadriceps and hamstring muscle strength to be able to maintain this low level stance. From the present study sword velocity was also determined by left and right hip flexion, suggesting that fencers should focus their training on increasing their flexibility of hip flexors such as iliopsoas and rectus femoris. Future research should therefore focus on implementing strength and conditioning programmes to strengthen the hamstring and quadriceps to determine whether sword velocity is increased. In addition research could be implemented to determine whether sword velocity is augmented with increased flexibility of the hip flexor muscles.

Using the information from this study, further research is warranted. Previous analyses have demonstrated that the anthropometric, flexibility and concentric force development parameters are linked to the development of velocity during lunge movements [5]. Future research should therefore consider an integrated approach that combines kinetic, kinematic and anthropometric measures which may provide more insight into the performance characteristics of the lunge movement in épée fencing. Whilst this study has identified key movement strategies linked to peak performance in a fencing lunge, it should not be assumed that by adapting movement strategies of individual fencers to those identified as being more desirable within this study will necessarily improve performance. Therefore it is recommended that future research should be undertook employing a movement strategy intervention in a group of fencers to identify the effects of changes in rear lower extremity's hip and knee movements as well as fore lower extremity's hip movements on sword velocity.

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