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Using Wearables to Monitor Trunk Kinematics and Accuracy in the Sport of Axe Throwing: A Pilot Study

Stuart A Evans [1,*] and Rodrigo Bini [2]

[1] Faculty of Health, Charles Darwin University, Darwin, NT 0815, Australia
[2] La Trobe Rural Health School, La Trobe University, Bendigo, VIC 3550, Australia; rodrigo.bini@latrobe.edu.au
* Correspondence: stuart.evans@cdu.edu.au

Abstract: The sport of axe throwing has gained popularity. Axe throwing is defined as a striking sport in which competitors are required to throw an axe with accuracy and appropriate velocity. However, evidence on the role of the trunk center of mass (CoM) in axe throwing, based on in-the-field experimental settings, is lacking. The aim of this study was to understand the variation in the magnitude of trunk CoM acceleration between male and female axe throwers and its relationship to throwing accuracy. The sample consisted of 10 adult axe throwers (five males: 35.9 ± 7.5 years; five females: 25.2 ± 3.2 years) of varying skill level and experience. The axe throwers completed five single-handed overarm axe throws using their right hand. The accuracy of the axe throws was recorded, along with CoM acceleration. The overall magnitudes of trunk CoM acceleration were significantly different between the male and female axe throwers (male CoM acceleration vector: 3.6 ± 1.1; female CoM acceleration vector: 2.2 ± 0.4; $p = 0.001$), with males recording a higher level of accuracy (males: 76%; females: 36%) in the axe throwing task combined with greater magnitudes of vertical acceleration. Female kinematics of the trunk were observed to have significantly higher magnitudes of mediolateral acceleration (3.55 ± 1.78, $p = 0.016$). The overall results identified that the vector magnitude of trunk CoM acceleration was significantly correlated ($r = 0.87$) to performance accuracy in the male throwers. It is suggested that axe throwers should consider using trunk CoM acceleration as a viable performance metric.

Keywords: axe throwing; center of mass; wearables; trunk kinematics; acceleration

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1. Introduction

Axe throwing is a target striking sport that is characterized by complex movements that require the contribution and sequential activation of body parts through a kinetic chain or link system. Axe throwing shares similarities with archery in that competitors must aim an object at a circular target with the objective of accurately hitting the center of the target (i.e., the bullseye). Points are then allocated based on where the axe hits the board, with maximum points awarded (five points) for landing the axe in the center of the board. Although a relatively new competitive sport, the biomechanics of throwing have been extensively studied dating back to the 1980s [1,2]. While increased sophistication of three-dimensional (3D) motion capture and complex data analysis have engendered a more nuanced understanding of throwing mechanics, the fundamental principles have remained unchanged [3]. However, knowledge concerning the biomechanics of axe throwing, specifically the kinematics involved, remains relatively unknown.

The axe throwing movement follows a circular path around the shoulder joint. During the throwing movement, the axe changes its angle to the ground ($\Delta\varphi$). Once the axe is released, it continues to rotate around its own center of gravity with the same angular velocity it had during the throwing movement. The rotation of the axe around its center of gravity is influenced by how fast the participant changes the angle of the axe (i.e., $\Delta\varphi$) during the throwing motion.

The growth in axe throwing has seen a subsequent increase in participation rates. Alongside the establishment in 2016 of the International Axe Throwing Federation (IATF), elite throwers now compete in international events. Nevertheless, given the relative novelty of axe throwing as a competitive sport, there exists a significant research gap in understanding the kinematic parameters in axe throwers of different abilities, such as elite and recreational throwers, and potential differences between male and female throwers. Accordingly, enhanced knowledge regarding the kinematics of axe throwing may assist in enhancing performance and overall accuracy of the throwing action. Important key performance indicators in the literature to date include shoulder and elbow torque and kinetic chain function [1–3], as measured by trunk rotation timing. Adequate rotation of the trunk is important given the necessity to assist in the transfer of power to the throwing arm. These factors, or key performance indicators, remain largely unexplored in what is a burgeoning sport.

The one-hand overarm axe throw is a commonly used technique that is typically characterized by three phases: A wind-up phase (arm circle swing phase), a rotational phase (upper body rotation), and a terminal release phase (drop phase) (Figure 1).

Figure 1. Illustration of the motion involved during the one-handed overarm axe throw.

The importance of trunk strength and endurance in overarm throwing is suggested to be vital for both performance outcomes and injury prevention [4,5]. These studies have also indicated that trunk contributions are important for both the demonstration of high throwing velocity and improving throwing velocity. Thus, the notion of enhancing trunk performance characteristics in throwing may augment the process of attempting to improve throwing velocity.

According to Putnam [6], throwing and striking movements are generally classified according to their proximal-to-distal sequencing. The proximal-to-distal sequencing of striking and throwing motions can be described either by the characteristics of the technique's linear velocities of segment endpoints, joint angular velocities, or segment angular velocities. In this regard, proximal-to-distal sequencing is determined by the successive occurrence of segmental velocity extrema. A transfer of velocity from distal to proximal is critical in maximizing distance in throwing [7,8]. Theoretically, increased trunk motion may allow more energy to be transferred from the trunk to the throwing arm, and eventually to the axe, which may lead to an increase in velocity.

The trunk musculature includes the rectus abdominis, external oblique, internal oblique, and transverses abdominis. The roles of this musculature in throwing are to promote dynamic stabilization, rotation, lateral bending, and flexion/extension of the trunk [4]. The magnitude of the center of mass (CoM) acceleration is a proxy measurement for the impact forces experienced at the trunk that is commonly used by clinicians and researchers. The trunk and the theoretical CoM transfer and control force and motion in an integrated kinetic chain and are important in throwing tasks. The acceleration of the trunk CoM occurs in three dimensions, often referred to with respect to a local CoM coordinate frame: Axial (vertical), anterior–posterior, and mediolateral [9].

In this way, the body system may be characterized, from a mechanical perspective, by its CoM. The CoM is the unique point in whose linear acceleration is determined only by the total external force acting on the system. When applied to the CoM, such force causes a linear acceleration without angular acceleration. Microelectromechanical system (MEMS) technology is the technology of microscopic devices, which typically incorporates accelerometers, gyroscopes, and a magnetic field sensor (magnetometer). This technology allows one to infer motion of the CoM via magnitudes of trunk CoM acceleration based on different forms of human movement (e.g., [10,11]).

To be successful in competition, axe throwers must achieve appropriate changes in upper body movement, including angle of release, projection height, and release speed, to optimize the throwing velocity of the axe. In this regard, general throwing is a goal-related task and, depending on the objective, the velocity and kinematic profiles change accordingly [12]. Yet such kinematic profiles are subject to change depending on both the gender and elative skill level and experience of the thrower.

Akin to other throwing sports, the end effector (e.g., hand/racket) velocity profiles depend on the skill level of the thrower [13] and the throwing technique [8]. Though, to the best of our knowledge, no research has addressed the idea of attempting to measure trunk kinematics via accelerations of the CoM or determine its effect on performance characteristics in axe throwing. Additionally, no study has examined the differences in trunk kinematics between male and female axe throwers of varying skill levels for performance purposes. This directs us to the question: What changes to trunk CoM acceleration demonstrate appropriate magnitudes that are specific enough to promote accuracy in performance characteristics between male and female throwers? These data may provide an estimation of the efficacy of trunk performance in respect to producing a specific training effect for improving throwing performance. Therefore, the purpose of this study was to examine the magnitude of differential trunk CoM acceleration in male and female axe throwers of varying skill levels while they performed five overarm axe throws, and to compare the trunk CoM kinematics demonstrated in actual throwing performance.

2. Materials and Methods

This cross-sectional and observational pilot study design examined the magnitude of triaxial trunk CoM acceleration and thus upper torso kinematics in five sequential one-handed overarm axe throwing movements and compared with overall throwing performance, that is—throwing accuracy. A sample of ten (n = 10; 5 males and 5 females) right-handed axe throwers participated in this preliminary study, having given informed consent, with approval by the University Research Ethics Committee (HREC21114). All participants were members of the same semi-professional axe throwing team. All participants trained at least once per week and had previously played and/or competed in at least one scheduled axe throwing league game in the past regulation season. Participants were excluded from the study if they had any injury (acute or chronic) or illness at the time of the study that prevented them from exerting maximum effort. Both male and female players over the age of 18 years were asked to partake in this study. The participants were informed that they could withdraw from the study at any time without penalty. For the time of the study, all participants were in physically good condition and reported no injuries or pain. The athletes were of various performance levels. Each participant had at least one year of training experience. Two of the participants had previously qualified to represent Australia at the 2022 International Axe Throwing Championship (IATC) (held in Toronto, Canada).

All participants were right hand-dominant. Dominance was defined by the individuals throwing arm preference, which was self-determined and visually confirmed by the principal author once informed consent was received. Prior to testing, anthropometric details, including height and body mass, were recorded. Height and weight were measured without shoes to the nearest 0.1 cm and 0.1 kg, respectively [14]. The anthropometric and training characteristics of the participants were taken and recorded by the principal authors. The anthropometric measurements are depicted in Table 1.

Table 1. Descriptive statistics of 10 semi-professional axe throwers (5 males and 5 females). When chronological age, height, and mass were considered, a significant difference (p = 0.0121) between the genders was observed.

Gender	Mean ± SD	Min.	Max.
Males			
Age	35.9 ± 7.5	23	45
Body height (cm)	179 ± 4.9	168	183
Mass (kg)	81.9 ± 4.4	68	96
Weekly training (h)	6.5 ± 0.6	3	9.8
Females			
Age	25.2 ± 3.2	21	26
Body height (cm)	163 ± 1.6	155	167
Mass (kg)	68 ± 5.6	62	77
Weekly training (h)	2.1 ± 0.2	1.00	3.00

Testing was conducted during the start of the participants' ten-week competitive season (i.e., week 1). All testing of the axe throwers commenced at 1700 in their customary axe throwing venue to ensure that their regular and scheduled throwing activity pertaining to the season was not interrupted. Data were collected under similar environmental conditions (17–18 °C, 45–55% relative humidity). The participants wore a loose-fitting t-shirt or singlet combined with either short or sweat (tracksuit) pants. After completing the informed consent and health history forms, the participants were asked to perform a general and self-directed warm-up. The warm-up included dynamic upper body stretching that was combined with approximately six practice throws of the axe.

To assess the impact of the trunk CoM during the five axe throws, one inertial measurement unit (IMU) was manually placed to sit at each participant's spinous process (i.e., a total of 10 accelerometers were used). Specifically, the accelerometer was aligned with the lumbar five (L5) sacrum one (S1) position [15] with the y-axis in alignment with the cervical vertebra (Figure 2). The accelerometer was secured into a moisture-proof ziplocked metallic matte foil airtight bag (Ferenli, Miami, FL, USA). The bag was attached using double-sided adhesive tape to ensure fixation and to reduce unwanted movement. [15]. The magnitude of acceleration was measured using the ActiGraph GT9X + accelerometer (ActiGraph, LLC, Pensacola, FL, USA). This device (3.5 × 3.5 × 1 cm, 14 g) was initialized to record accelerations at a sampling frequency of 100 Hz. Orientation of the sensor was to capture data in the three orthogonal directions, specifically in the vertical (y, upward–downward), anteroposterior (x, forward–backward), and mediolateral (z, side to side) directions (in m/s^2). The raw accelerometry signals from the trunk CoM were downloaded and then converted from gt3x files to CSV format and saved and exported to Microsoft Excel. Raw data were then analyzed using the ActiLife software program (Version 6.13.4, ActiGraph, LLC).

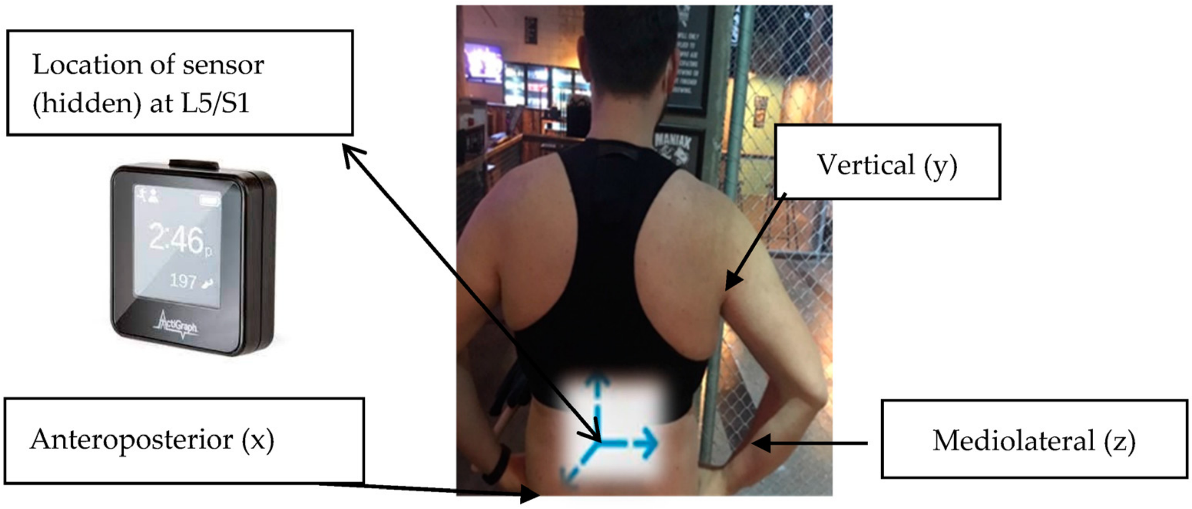

Figure 2. Location and orientation of the ActiGraph GT9X + accelerometer used on all participants.

2.1. Procedures

In this pilot study, the participants were required to perform five single-handed overarm axe throws using their preferred method and dominant hand (i.e., right hand) to grip the handle of the axe. The purpose of analyzing the five overarm axe throws was that in each regulation competition round, five throws per player are permitted (i.e., as stipulated by the IATF). Thus, to ensure consistency and familiarity, this criterion was kept. The single-handed axe throw required the participants to hold the handle of the axe with their right hand while facing the target board using a self-selected grip. The participant's right shoulder complex remained in extension while the elbow was in flexion. The axe was observed to be drawn to a position of approximately 135° shoulder flexion before the axe was released slightly prior to the shoulder reaching approximately 90° flexion. From this initial position, the participants moved their trunk in accordance with releasing the axe. Once the axe was thrown and hit the target board, the participants walked toward the target board to retrieve the axe, performing the movement again until the five repetitions had been completed. The accuracy of the axe throws, and the subsequent score, was recorded on an electronic scoreboard that was in the venue. All scores were verified by a qualified member of staff and then manually entered onto a log sheet (Microsoft® Excel® Microsoft Corporation Redmond, Washington, DC, USA version 2304 build 16.0.16327.20200) by the principal author. The participants were asked to perform the throwing action in their accustomed and characteristic style whilst aiming for the highest possible score—that is, without interference from the researchers. Therefore, to control and replicate a typical practice and competitive setting, the participants were asked to replicate their traditional routine.

2.2. Instrumentation

The mass of the axe used by the participants was 1.13 kg. The handle of the modern standard throwing axe was made from wood with a minimum length of 33 cm and a maximum length of 43.18 cm, based on measurement that commenced from the butt of the handle to top of the axe head (Figure 3). These dimensions complied with the rules and regulations stated by the IATF.

Figure 3. Dimensions of the axe used by the participants.

The players commenced the axe throw from the black line as shown in Figure 4. Specifically, when the throwers prepared for their throw, their left rear foot was positioned so that it was completely behind the black line with their right rear foot situated further backward and behind their left foot. The front of the black line was measured at 431.8 cm (170″) from the subframe of the target. The black line was aligned with the center of the bullseye so that when measured from the center of the black line, there was 66.04 cm (26″) on the left and right to be split evenly from the center of the bullseye. The black line from the target represented the point in which players were not allowed to take more than one step past while throwing an axe.

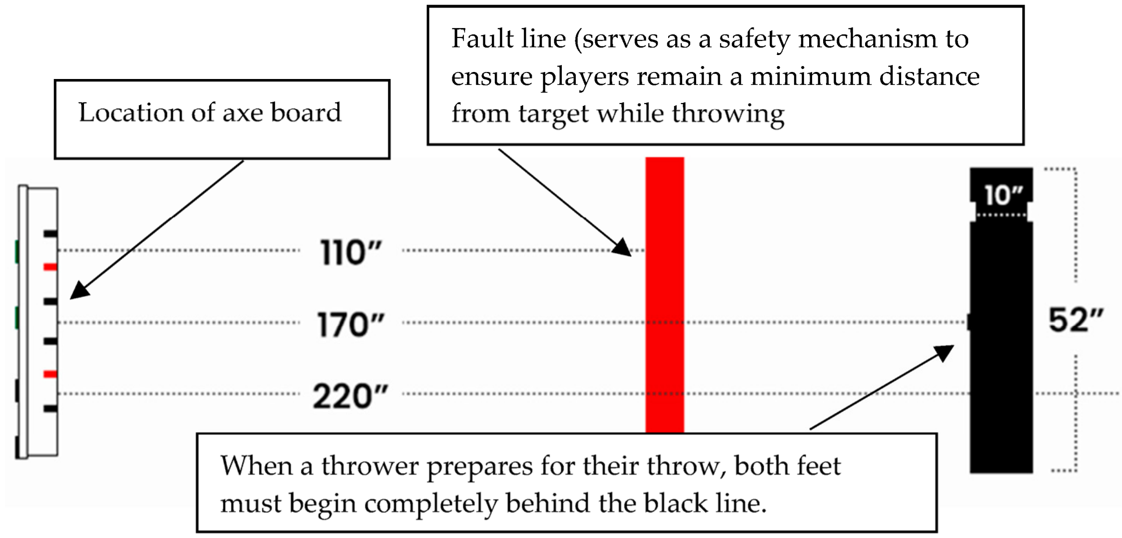

Figure 4. Lane dimensions permitted in the axe throwing task. The black line represents the point marker where the participants were required to stand and throw the axe.

To verify the accuracy of the sensor data output during the post-hoc process, all axe throwing motion was subsequently filmed, with raw data manually entered onto a participant log sheet. To achieve this, all throwing activity and angle approximation was continuously filmed using an iPhone (version 15.6.1) and iPad device (5th generation, version 15.7). The iPhone and iPad were located upon two tripods, whereby the cameras on both devices were positioned to capture each thrower's bilateral movement in the sagittal plane. The iPhone was placed on a tripod at a height of 55 cm and the iPad placed on a tripod at a height of 85 cm when on the floor. The throwing motion was recorded to enable manual synchronization during post-hoc processing. Thus, the timing of the throws was also manually recorded using a conventional stopwatch. The timings were then entered onto a log sheet (Microsoft Excel; 4.90.4, build 6470.27615). The raw acceleration files were converted to time-stamped CSV files and exported into Microsoft Excel for processing and analysis. The participant log sheets with the observed start and end times of the throwing activity were utilized for identifying the throws in the time-stamped CSV files.

2.3. Scoring

In line with the IATF's standardized rules pertaining to competition, the scoring (points) values were classified for participants placing the axe in: (1) The bullseye or red ring was worth 5 points; (2) the black ring was worth 3 points; (3) the outer or blue ring was worth 1 point. The green dot in each upper corner of the target (known as the Clutch) was not included in this protocol (Figure 5).

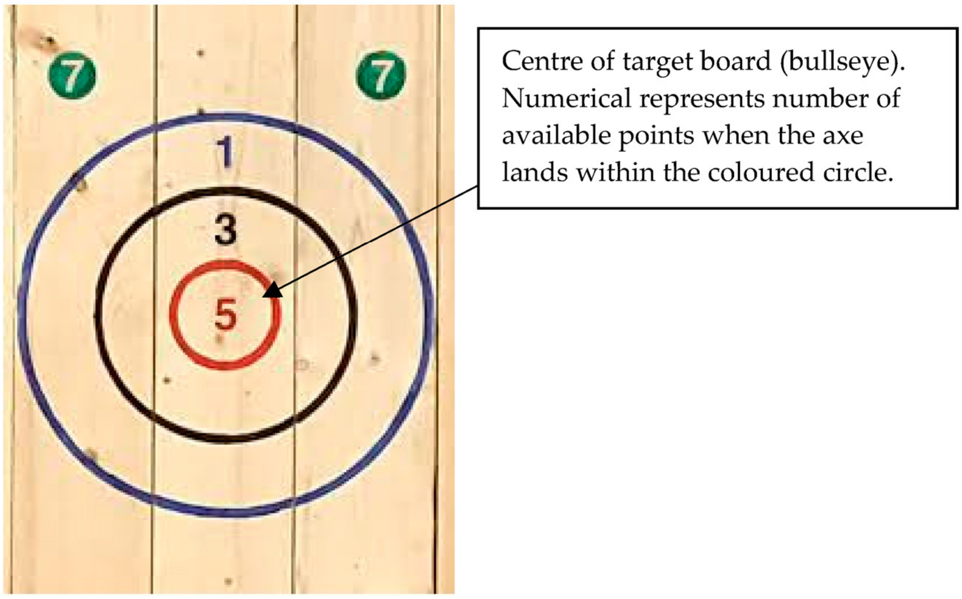

Figure 5. Target board and representation of the points allocated. The center of the bullseye measured 160.2 cm from the floor.

2.4. Statistical Analysis

The normality of the data was assessed by the Shapiro–Wilk test using the Analyze-it statistical package (version 4.92, Leeds, UK). As the data were not normally distributed, a nonparametric Kruskal–Wallis test (H) was performed to assess the magnitude of triaxial acceleration in the overarm throw between male and female throwers. A Wilcoxon test was used to assess participant differences in chronological age, height, and mass between genders, as well as differences between throws relative to acceleration magnitude in order to obtain the exact p-value. To investigate possible correlations between overhead throwing accuracy and the magnitude of trunk CoM acceleration in male and female participants, the mean vector magnitude of the five axe throws were calculated and assessed. Spearman's rank correlation coefficient, denoted as rs, was used, given that the values were not normally distributed to analyze the differences between the vector magnitude of the triaxial acceleration of the trunk CoM and the dependent variable of one-hand throwing accuracy. A covariance measure was applied to quantify the direction of the relationship between throwing accuracy and the acceleration vector. Confidence intervals at 95% were applied to provide an estimated variation between the magnitudes of triaxial acceleration. Furthermore, the coefficient of variation (CV)—that is, the ratio of the standard deviation to the mean—was used to analyze the level of dispersion around the mean magnitudes of triaxial acceleration of the trunk. To assess performance accuracy, these measurements are presented as a percentage of successfully performed axe throws based on the scoring system outlined in Section 2.3. The importance level was defined as $p < 0.05$.

3. Results

The descriptive statistics for the average mean magnitudes of the male and female axe throwers in trunk CoM acceleration are presented in Table 2. The CV defines that the greatest within participant differences occurred mediolaterally. The mediolateral acceleration also contained the widest difference in the 95% confidence interval when compared to the other channels (e.g., the difference from upper and lower bounds was 2.01).

Table 2. Mean and standard deviation (±SD) of the magnitude of trunk CoM acceleration in five one-handed overarm axe throws for 10 participants (5 male and 5 female). Acceleration data presented in meters per second per second (m/s^2). CV = coefficient of variation; CI = confidence interval at 95%. * Significant at $p < 0.05$.

Direction and Axis	Throw 1	Throw 2	Throw 3	Throw 4	Throw 5	Kruskal–Wallis (H)	95% CI Lower Upper	CV	Difference between Throws
Anteroposterior (x)	0.416 ± 0.03	0.515 ± 0.02	0.651 ± 0.03	0.405 ± 0.04	0.418 ± 0.03		0.397–0.555	23.2%	0.016 *
Vertical (y)	0.798 ± 0.03	0.792 ± 0.03	0.831 ± 0.08	0.802 ± 0.07	0.798 ± 0.03	4.00, p = 0.406	0.174–1.863	16.5%	0.703
Mediolateral (z)	2.978 ± 0.23	2.791 ± 0.20	2.912 ± 0.23	2.898 ± 0.23	2.787 ± 0.31		1.847–3.852	49.2%	0.012 *

Regarding the performance and accuracy levels between genders, the mean values of the center target score (accuracy performance score five) for the female group were statistically, and significantly, different between the five throwers. In contrast, a non-significant result was observed in the five male throwers, while throwing accuracy was significantly correlated with the vector magnitude of triaxial acceleration (Table 3).

Table 3. Mean ± SD magnitudes of trunk CoM acceleration and throwing accuracy based on the vector indices of trunk CoM acceleration magnitude in female (n = 5) and male (n = 5) axe throwers during the performance of five one-handed overarm axe throws. Acceleration data presented in meters per second per second (m/s^2). Spearman's *rs* correlation between vector magnitude of triaxial acceleration and throwing accuracy. * Significant at $p < 0.05$.

Gender	Mean Vector ± SD	Covariance	Accuracy Ratio	Spearman's *rs*	Difference between Genders (p)
All participants (n = 10)	2.91 ± 1.2	0.43	58.5%		
Male (n = 5)	2.14 ± 0.12	0.20	76%	0.67	<0.0001 *
Female (n = 5)	3.55 ± 1.78	3.17	36%		

The analysis of the anteroposterior, vertical, and mediolateral magnitudes of trunk CoM acceleration of the male and female axe throwers (Table 4) indicates that while vertical motion was greater in the male throwers, this was apparently offset by the significant reduction in mediolateral motion when compared to the female axe throwers. The difference in the coefficient of variation in mediolateral trunk movement was 44.6%. The excessive sideways motion of the trunk may have impacted the female throwers' accuracy.

For further comparison, an individual trial representing a male and female thrower performing a standard one-handed overarm axe throw is presented visually using raw trunk CoM acceleration outputs (Figure 6). Among the identified issues were the following: Reduced vertical acceleration at the beginning of the throw in the sensor signal in the female thrower and greater separation of the three-acceleration channels at the one second mark in the female thrower.

Table 4. Mean ± SD magnitudes of trunk CoM acceleration differences in female (n = 5) and male (n = 5) axe throwers during the performance of five one-handed overarm axe throws were determined. CV = coefficient of variation. Where AP is anteroposterior, V is vertical, and ML is mediolateral acceleration in meters per second per second (m/s^2). * Statistically significant at $p < 0.05$.

Gender	Mean ± SD AP (x) m/s^2	CV	p	Mean ± SD V (y) m/s^2	CV	p	Mean ± SD ML (z) m/s^2	CV	p
Male	0.463 ± 0.12	27.4%	<0.0001 *	1.293 ± 1.87	10.6%	0.125	2.14 ± 0.05	5.6%	0.016 *
Female	0.489 ± 0.10	21.3%		0.395 ± 0.745	18.5%		3.550 ± 1.78	50.2%	

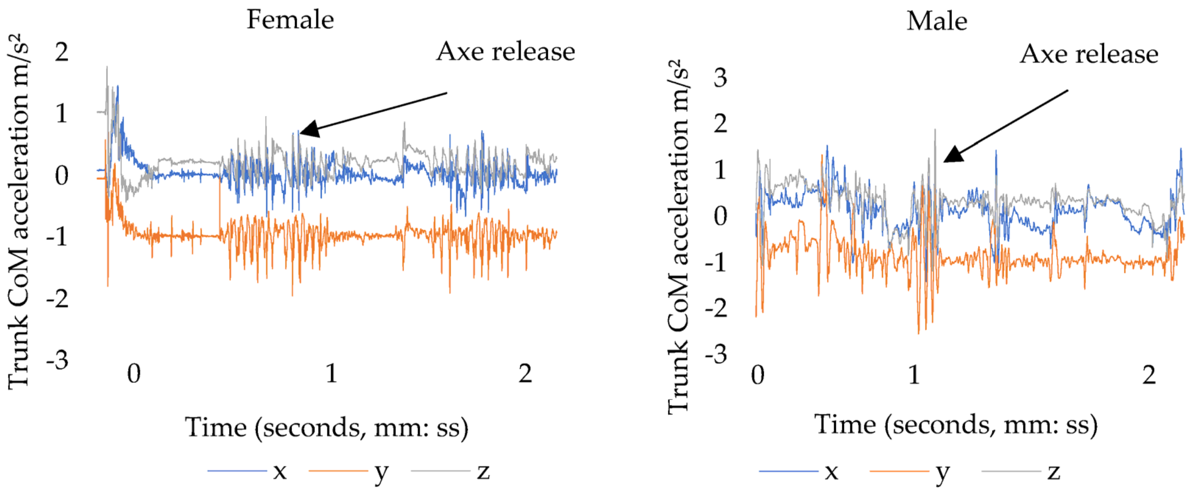

Figure 6. Representative example of the magnitudes of trunk CoM acceleration in a female (**left**) and male (**right**) during performance of one overarm axe throw. Where x is anteroposterior, y is vertical, and z is mediolateral acceleration of the trunk CoM.

4. Discussion

The present study, a pilot project in what is a burgeoning competitive sport, investigated the effect of five one-handed overarm axe throws on performance accuracy and the magnitude of trunk CoM acceleration in male and female axe throwers of varying skill levels. Specifically, the magnitudes of anteroposterior (AP), vertical (V), and mediolateral (ML) acceleration of the trunk in five male and five female axe throwers were investigated while the participants kept all other conditions fixed, including the total duration of the task, which in this case was equal to approximately two minutes. To assess trunk CoM acceleration, the minimum and maximum magnitudes of triaxial acceleration were analyzed in all participants using data from a wearable sensor. Data were obtained in the field using an accelerometer, iPhone, and iPad to capture all throwing movements in what was representative of a typical competitive setting. To the best of our knowledge, this is the first study to explore these topics in what remains an underrepresented sport in terms of applied field-based kinematic research. The results from the current study indicate significant variation in anteroposterior and mediolateral acceleration of the trunk CoM during the five one-handed overarm axe throws, thus denoting changes in trunk motion in both male and female throwers (Table 2). Furthermore, changes in trunk CoM acceleration during each of the five axe throws were analyzed. These changes revealed a somewhat transient yet fluctuating approach to trunk CoM motion with a large magnitude of mediolateral acceleration observed during Throw 1 (2.97 m/s^2, Table 2) and a lesser mediolateral magnitude seen during Throw 5 (2.78 m/s^2, Table 2). While a significant difference in mediolateral acceleration was seen, the variation within both male and female throwers was notable at

49.2%. One possible reason for the higher acceleration magnitude observed during Throw 1 could be due to participants essentially warming up and trying to stabilize the trunk in preparation for the subsequent throws. Although the participants performed a self-selected warm up, when faced with a competitive situation (e.g., throwing repetitively whereby accuracy is measured), a modicum of mediolateral sway may have occurred initially until greater stability is achieved. More research to confirm this proposition is required, however. Moreover, the mediolateral acceleration variation contrasted with that of 23.2% that was observed in the anteroposterior direction and 16.5% in the vertical direction.

Preceding electromyographic studies comparing different trunk flexion speeds showed that the highest exercise speeds require the highest activation levels of flexor and extensor trunk muscles [16]. Correspondingly, research has primarily focused on the effect of hip flexion, supported segments, arm and hand position, knee and hip position, movement of the upper body vs. lower body, and the use of equipment on trunk muscle response [17]. However, looking at the broader ability of the motor system and trunk muscular to maintain stability during the axe throw, throwing ability is affected by a myriad of variables, including experience, strength, throwing velocity, release height, training, and biomechanical efficiency. Thus, because both the mediolateral and anteroposterior acceleration of the trunk CoM trended toward significant variations between the participants, an interplay exists between the upper and lower magnitudes in both the anteroposterior and mediolateral directions. The primary influence might be a mediolateral shift, which may act as a lead axis, progressively leading to eventual inferior axe throwing performance.

The anteroposterior and vertical directions, which are mainly involved in symmetrical motion during the throwing phase of the axe throw, were observed to have the widest dispersed acceleration in relation to the participant group mean. It is possible that the differences in these acceleration channels could be due to the participants' expertise, or lack of, in performing axe throwing. Correspondingly, in this case, a lower level of expertise/training may contribute to a reduction in accuracy, possibly when the release speed intensifies. Traditional studies on the speed–accuracy trade-off in aimed movements found higher errors when the movement was performed at a faster pace [18,19]. Therefore, the lack of task experience in some participants and the relative lack of trunk strength may explain the significant effect of medial–lateral sway. Nevertheless, the interaction between trunk motion control, task experience, task constraints, and performance must be explored in future studies.

The results suggest that some of the throwers, namely, those with more experience, may have greater control of their vertical acceleration. This would, in turn, enable greater efficiency when aiming the axe at the center of the target (i.e., the bullseye). The important factor here was that the magnitude of change between throws one and five remained relatively stable, as evidenced by the non-significant result (Table 2). As Figure 2 shows, the linear vertical variability increased during throws three and four. Taking into account fluctuations that reflect the neuromuscular system's response to control the body motion [20], the results from the current study may suggest that some of the participants produced a greater neuromuscular effort in order to control, or stabilize, the trunk motion during the throwing action.

Some additional considerations should be made regarding the throwing motion, however. If the thrower's goal is to maximize the length of the throw, he or she must find the optimal combination of the three variables (speed, angle, and height of release) [21]. With the axe throwing technique deployed by participants in the current study, even considering all of the subjective technical interpretations, the release height may be strongly conditioned by the anthropometric characteristics of the thrower. These results could suggest that alternations to release height and/or release angle altered the trunk and magnitude of acceleration. However, to entirely understand the development and impact that axe throwing velocity has on the trunk, three parameters must be taken into account: The tangential velocity, the angular velocity, and the radius of instantaneous rotation.

Looking at the gender differences, the results showed that the magnitude of trunk CoM acceleration once again varied, notably in the ML direction, underscored by a greater coefficient of variation in the female throwers compared to the males (i.e., 52% compared to 5.2%). To this end, core stability and core strength are routinely discussed in the literature or coaching circles as important to throwing performance while lacking depth and breadth of research to confirm this claim [22]. The location of the CoM of the axe thrower system in both genders may also differ during the initial and release phases of the throw. In the hammer throw, it has been found that women are more upright during the throw due to smaller body mass and a lighter implement [23], with less energy used by women to counter the forces acting upon them as men due to the lighter ball, lighter body weight, and higher CoM [24]. Despite obvious differences between axe and hammer throwing, it could be that the female axe throwers experienced greater mediolateral movement and insufficient vertical displacement of the CoM during the pre-release phase of the axe throw—that is, prior to moving into shoulder flexion (Table 4). Moreover, this could lead to increased energy expenditure (i.e., increased O_2 cost) that is not beneficial for throwing velocity, thereby further impacting throwing performance outcomes. Furthermore, it was expected that the mass of the axe would influence the velocity and release angle of the axe, as well as motor performance for the novice female axe throwers. While the axe dimensions, inclusive of mass, where standard for all throwers, it could be that for some of the less-experienced female throwers, the axe mass constraint caused them to change their motor control strategy. Thus, it is plausible that this would significantly increase mediolateral CoM acceleration and anteroposterior motion with a decrease in the vertical axis compared to the male throwers. This underscores the need for a strong and stabilizing trunk to maintain throw performance in both genders. It is possible to speculate that a change in throwing mechanics occurred due to higher levels of mediolateral motion and lower levels of vertical motion.

A weak correlation ($r = 0.31$) between trunk CoM and throwing accuracy was observed in all ten participants. However, in contrast, a strong correlation of trunk CoM acceleration magnitude in the male axe throwers ($r = 0.87$, Table 3) was observed, along with a higher proportion of accuracy—that is, the number of times the center target was hit (i.e., the bullseye). Of the five one-handed overarm axe throws that were investigated in this study, the mean vector value for the male throwers was the outcome variable with the largest unexplained between-subject variability, suggesting that random variability or other variables than those investigated might have considerable effect on the result. Even so, the normalized covariance for the male throwers suggested that the measurement of the relationship between accuracy and the vector magnitude for trunk CoM acceleration was strong. This is in agreement with Graham and colleagues [25] in that an increase in stability consistent with what was also shown indicated that trunk stability increases in tasks that require more muscle exertion and trunk stiffness.

The extra body mass and the increased athlete height in the male throwers may be an advantage in throwing distance and therefore accuracy. These two variables impact the throwing variables of velocity and release height [23]. The extra body mass of the males (81.9 kg in males compared to 68 kg in females) may have granted the male throwers to position their trunk more effectively in order to generate greater angular momentum while maintaining balance as the axe throw progresses toward release. Moreover, increased athlete height allows a greater release height, which slightly increases flight time for men [23]. This is akin to shot putting, where males have a greater release height than females [26]. The result of this increased release height is a slightly longer throw, assuming all other factors are maintained. In this regard, a premise to consider is that periodized core strength training, especially during the off- and pre-season, as well as into a thrower's competitive season, has the potential to optimize performance by preventing unwanted or inefficient trunk motion.

The act of throwing itself transfers tremendous power throughout the kinetic chain. This requires motor skill to achieve precision control and force generation. Furthermore, joint coordination is related to the stability and accuracy of movements for precision control, while joint correlation is related to transfer of forces and movements for force generation [27]. In the existing experiment, the center of the bullseye sat in the center of the wooden board and measured 177.8 mm in diameter. As a result, tiny displacements and variability in trunk CoM acceleration during throwing, such as excessive vertical lift of the shoulder, elbow, or axe during the release moment, can significantly influence the magnitude of CoM performance, even though elite and more experienced throwers could theoretically compensate for these variabilities. However, the kinematics of the proximal joints (elbow and wrist) and their respective influence on an axe throwing tasks warrants further research.

Some limitations require attention. The relatively small sample size limits the generalizability of the findings. Further studies will make it possible to enlarge the sample size to analyze data differentiated by gender and anthropometric factors, to evaluate the effects of asymmetric tasks, and to evaluate throwers presenting with a preference of using the left hand to instigate the throw. However, the relative newness of axe throwing as a competitive sport has very limited participants practicing at the elite or semi-professional level, which reduces the population and potential sample. The limitations to the direct linear acceleration methods using a sensor are the inaccuracies that can occur as points at the extremes or slightly outside of the calibrated space are analyzed [28]. The best way to minimize this problem is to have well-distributed control points within the calibrated space [29]. It is presumed that inaccuracies were minimal considering the controlled calibrated space in the indoor axe throwing facility where the current experimentation took place, and that the sensors were securely fastened to the participants to limit unwanted movement.

Lastly, in accordance with the throwing assessment protocol, a typical and familiar axe throwing venue was selected to analyze axe throwing performance to ensure valid, real-world applicability of the current results. Another approach to investigate the magnitude of trunk CoM acceleration would include analysis between competitive players longitudinally—that is, over the duration of a competitive season. Future approaches, especially ones that use more elaborated movement sequences could employ more complex measures, for instance, based on time series analysis or entropy. This further underscores the probable importance of maintaining a stable and strong core musculature, via specific and periodized strength endurance training, for preserving or improving throwing performance.

5. Conclusions

This field-based pilot study successfully used a noninvasive wearable sensor to objectively assess the magnitude of trunk CoM acceleration in male and female axe throwers. In summary, significant differences were observed in performance with female axe throwers displaying more mediolateral trunk CoM acceleration and were less accurate compared to male axe throwers. The vector magnitude of trunk CoM acceleration was significantly correlated to better performance—that is, greater accuracy in hitting the bullseye in the male axe throwers despite a higher magnitude of vertical acceleration. With current testing protocols showing limited or equivocal practical results in axe throwing performance, strength and conditioning coaches should ensure adequate trunk training exercises are used to increase axe throwing performance. It is suggested that axe throwers should consider using trunk CoM acceleration as a viable performance metric.

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