Shot Trajectory Parameters in Gold Medal Stationary Shot-Putters During World-Class Competition

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The parameters of the shot’s trajectory were reported for male and female gold medalists (classes F52, F53, F54, and F55) who competed at the 2000 Paralympic Games and the 2002 International Paralympic Committee (IPC) World Championships. The specific objective was to determine the magnitude of differences in these parameters across classes and genders. The release velocity of the shot increased with the performance and the classification for both males (8.30 m/s – 9.96 m/s) and females (4.58 m/s – 8.50 m/s). The measured angle of the shot’s trajectory at release also increased with the performance and the classification for both males (27.54° – 32.47°) and females (9.02° – 34.52°). The position of the shot from a fixed reference point at release revealed a similar trend for both males (2.01 m – 2.68 m) and females (1.16 m – 1.98 m), although it was weaker.

Kinematic analyses of the throwing techniques of elite stationary shot-putters are commonly conducted in routine observations and sport research (Ariel, 1979; Chow & Mindock, 1999; Dessureault, 1978; Lichtenburg & Wills, 1978; McCoy, Gregor, Whiting, & Rich, 1984; O’Riordan and Frossard, 2006; Pagani, 1981; Zatsiorsky, Langa, & Shalmanov, 1981). An overview of the biomechanical parameters, level of performance of the athletes recorded, recording environments, and outcomes of previous studies is provided in Figure 1.

Some of these analyses focused on parameters underlining either the sequence of actions taken by the athlete leading to the release of the shot (e.g., spatial and temporal characteristics of backward and forward thrust, range of motion, linear and angular momentum of each segment) or the shot’s trajectory at the instant of release (e.g., position, speed, and angle of shot). Both data sets were reflective of the functional outcomes and throwing techniques of the athletes. Consequently, they

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Frossard et al. have been used by sport scientists, coaches, athletes, and classifiers to establish the link between disability, performance, and classification dividing athletes according to their functional level (Chow, Chae, & Crawford, 2000; Higgs, Babstock, Buck, Parsons, & Brewer, 1990; McCann, 1993; Tweedy, 2002; Vanlandewijck & Chappel, 1996; Williamson, 1997).

Ultimately, these studies contributed to improvement of training programs of stationary throwers as they provided coaches and athletes with a better understanding of throwing technique as well as strength and fitness requirements. These studies also contributed to increase fairness of stationary throwing events through a refinement of the classification system as well as the rules about the throwing posture and design of the throwing frame.

**Figure 1** — Overview of the biomechanical parameters (A), the level of performance of athletes recorded (B), the recording environments (C), and outcomes (D) of previous and present studies of elite stationary shot-putters.
These studies presented a number of limitations, however. The participants were male. No studies focused on elite female stationary shot-putters. Most of the participants had emerging or elite status, which included those who represented their countries in major events such as the Paralympic Games. Occasionally, a study included a gold medalist or a world record holder in a given class. The relationship between the classification and the kinematic parameters shown by studies conducted prior to 2000 is obsolete, as the classification was updated for the 2000 Paralympic Games (Sydney, Australia). Nonetheless, the positive correlation between the current classification and the parameters is likely to be sustained as both classifications are based on the level of functional outcomes of the athletes. Most of these kinematic analyses were conducted from video taken during training. This provided the advantage of easily accommodating usual experimental requirements including the use of active or passive markers, the positions of cameras, and the number of attempts recorded. These studies attempted to simulate the conditions of a real event. It is difficult to fully replicate, however, the environmental factors of a world-class event, including the stress and pressure due to the presence of other opponents, mass-media, referees in charge of strictly applying the rules, and the use of official equipment to anchor the throwing frame (i.e., the use of a metal plate on the ground rather than pegs). Consequently, these data may only be somewhat representative of the performance of elite athletes while competing in a world-class event. For instance, the elite shot-putters participating in Chow et al.’s 2000 study performed on average $15 \pm 9\%$ less than their personal best.

In conclusion, sport scientists, coaches, athletes, and classifiers can only rely partially on data provided in the literature for a sound understanding of the current performance of medalist stationary shot-putters (Frossard, O’Riordan, Goodman, & Smeeathers, 2005). As pointed out by Chow et al., 2000, “More quantitative data, especially those collected during major competitions, are needed for the development of a data base on performance characteristics” (p. 329). To date, results focusing on data collected during world-class events have been mainly reported in abstract form. For instance, Frossard, Schramm, and Goodman (2003) have presented a preliminary study providing examples of the parameters of the shot’s trajectory during the 2002 IPC World Championships (Frossard et al., 2003). Their studies presented a number of shortcomings, however, including the small size of the population (only three Australian male athletes), the modest level of performance (ranking 9th, 6th, and 5th), and the scattered range of classes considered (classes F34, F52, and F55).

Thus, the present study aimed at extending the work initiated by Frossard et al., 2003 by reporting the parameters of the shot’s trajectory for male and female gold medalists during world-class events. The specific objective was to provide the magnitude of differences in these parameters across classes and genders.

**Method**

**Participants**

Video filming was conducted during two world-class events, the 2000 Paralympic Games, Sydney, Australia (Classes F53 and F55 Men, Classes F52, F54, and F55 Women) and the 2002 International Paralympic Committee (IPC) World Championships, Lille, France (Classes F52 and F54 Men).
Only the best attempt of the best four men and three women stationary shot-putters in four consecutive classes (F52, F53, F54, and F55) were analyzed in this study. Each athlete was classified according to the International Stoke Mandeville Wheelchair Sports Federation classification system (updated in 2000; Laveborn, 2000).

Female classes F52 and F54 were combined and competed together due to the small number of athletes at the Paralympic Games in both classes. Consequently, only one gold medal was given for this event. The best performance for each class was considered separately in this study, however. The shot-put event for class F53 female was cancelled due to lack of athletes.

The Sport Science Committee’s policy with respect to research conducted at IPC sanctioned events does not allow researchers to interfere with athletes’ competition and athletes’ preparation to competition. Consequently, no demographic or anthropometric information was recorded in this study.

Data Processing

Previous publications have already reported in depth some of the practical obstacles inherent in video recording during a world-class event (i.e., number and position of cameras, impact of disturbing factors, no interactions with participants, quality control procedure; Frossard, O’Riordan, & Goodman, 2005; Frossard, O’Riordan, Goodman, & Smeathers, 2005; Frossard, Stolp, & Andrews, 2006). Thus, only the key elements will be presented here.

Step 1: Camera Setup. Each attempt was recorded using one digital video camera (SONY, Digital Handycam DCR-TRV15E) set at a sampling rate of 25 Hz. The camera was placed approximately 1.10 m high at a distance between 8 to 10 m perpendicular to the length of the plate. The camera was placed relatively close to the plate in order to reduce the possibility of intrusion in the field of view from TV crews, other equipment, and/or referees. The angle between the optical axis of the camera and the sagittal plan was approximately 90°. The field of view of the camera included the full-length (2.29 m) and full-width (1.68 m) of the plate on the ground (Figure 2). The field was also enlarged in the direction of the put to secure the recording of at least the first five frames of the shot’s aerial trajectory. The zoom was occasionally used to optimize the appropriate field of view. This camera position resulted in a pixel resolution ranging from 0.95 cm to 1.85 cm, depending on the camera’s position and zoom setting.

Step 2: Video Recording. The seven attempts were recorded on MiniDVs. The duration of the video recording of each attempt was approximately seven seconds. The recording started when the referee handed the shot to the athlete and ended shortly after the shot landed on the ground. A customized calibration frame (2 m length x 1.5 m height x 1 m width) including 43 control points placed on top of the plate was recorded at the beginning and at the end of each event.

Step 3: Video Digitizing. The video recordings of the calibration frame and the attempts were digitized at 50 Hz using Digitizer 5.0.3.0 software (SiliconCOACH Ltd, Dunedin, New Zealand). The 50 Hz sampling frequency was achieved by deinterlacing each video frame.
Step 4: Tracking of the Shot’s Release. The Digitizer 5.0.3.0 software was used to track frame-by-frame, the center of the shot, the distal end of the middle finger, the position of the wrist, and the origin of the 2D Global Coordinate System (GCS: O, X, Y). The GCS was located at the mid point in front of the throwing plate along the marked arc that is used by the referee to measure the performance, as presented in Figure 2. The tracking started approximately ten frames before the estimated release and ended five frames or more after, until the shot was no longer within the field of view. The two coordinates of the points tracked were imported into a customized Matlab software program (Math Works Inc, Novi, MI, USA). An operator used this software to select a combination of two positions of the shot, allowing the calculation of the parameters of the shot’s trajectory (Step 5). The first position corresponded to the instant of release, while the second corresponded to one of the three consecutive frames. This choice was made based upon the outcome of step 5 during the course of the iteration process described in the quality control section (Frossard, Smeathers, O’Riordan, Evans, & Goodman, 2007).

Step 5: Calculation of the Shot’s Trajectory. The software implemented the classic equations (Lichtenburg & Wills, 1978; Linthome, 2001) to calculate the trajectory of the shot, allowing the landing distance to be estimated. The calculated
performance was determined based on several parameters of the shot at the instant of release, including the following:

- The resultant, horizontal, and vertical components of the linear velocity;
- The resultant, horizontal (advancement) and vertical (height) components of the position; and
- The angle of the release of the trajectory.

The calculated performance was also corrected by the radius of the shot, as the official performance was measured from the landing mark on the ground closest from the GCS.

The optimum angle of release was computed using the speed and the height of release, as presented by Lichtenburg and Wills, 1978 and Chow et al., 2000. A positive angle difference indicated that the measured angle was inferior to the optimum angle. By definition, the optimum angle is calculated based on the assumption that the athletes could produce the same speed of release regardless of the angle, although it will depend on the functional potential of each athlete.

**Step 6: Comparison of the Official and Calculated Performance.** The calculated performance was compared with the official performance, corresponding to the distance measured by the referee during the event. The official performance was taken as the reference value.

**Quality Control**

A quality control procedure was applied, consisting of a number of iterations after the digitizing, processing the data through steps 4 to 6 until the difference between the calculated and measured performance was minimized (Frossard et al., 2007).

The outcomes of this procedure were reported in terms of error corresponding to the difference in meters between the official and calculated performance. The outcome was also represented by the calculation quality corresponding to the percentage of the absolute value of the calculation error in relation to the official performance, such as Calculation quality = 100 - (Abs[Error]/Official performance)*100.

**Data Plotting**

The calculated performance of the females and males in each class is presented in Figure 3. The performance increased linearly with the classification for all the female classes and between classes F53, F54, and F55 for the males. Consequently, one can assume that a given relationship between a parameter and the performance will also result in a similar relationship between this parameter and the classification. So, the kinematic data (the speed, the position, and the angle at release) were plotted in relation to the calculated performance rather than the classification.

A linear regression line between the distance thrown and the kinematic data was plotted separately for each gender. This line was chosen to give a simple illustration of the trend of the progression of the distance thrown in relation to kinematic data. This line does not indicate a linear relationship between the two axes since the assumption that the classes are proportionally distributed is yet to be validated.
Results

Accuracy (Table 1)

The error and calculation quality are provided in Table 1. The accuracy was superior to 94% for four attempts and only superior to 75% for three others (classes F53 and F54 Men, class F52 Women). The lack of accuracy for these classes was mainly due to the projection of the displacements out of plane movements of the shot onto the sagittal plane, as explained in Frossard et al., 2006.

Table 1  Outcome of the Measured Versus Predicted Distances for Each Class

<table>
<thead>
<tr>
<th>Class</th>
<th>F52</th>
<th>F53</th>
<th>F54</th>
<th>F55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error (m)</td>
<td>-0.01</td>
<td>0.82</td>
<td>1.33</td>
<td>0.38</td>
</tr>
<tr>
<td>Calculation quality (%)</td>
<td>99.93</td>
<td>89.14</td>
<td>85.09</td>
<td>96.85</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error (m)</td>
<td>-0.66</td>
<td>-</td>
<td>-0.05</td>
<td>-0.51</td>
</tr>
<tr>
<td>Calculation quality (%)</td>
<td>79.42</td>
<td>-</td>
<td>99.17</td>
<td>94.33</td>
</tr>
</tbody>
</table>
Calculated Performance vs. Classification (Figure 3)

The increase in performance between the classes F52 and F55 was 5.90 m for the females and 3.08 m for the males. The distance reached by the females in classes F52, F54, and F55 was 6.34 m, 4.05 m, and 3.52 m, respectively smaller to the males in the same class. Incidentally, class F55 women performed only 0.44 m less than class F52 men.

Speed of Release (Figure 4)

The horizontal component for the female gold medalist in class F54 was under the line of regression while the vertical component was above. Consequently, the resultant was on the line of regression of the other female athletes. The horizontal and vertical components, as well as the resultant of the velocity of the male in class F53, were slightly under the line of regression of the other male athletes.

The increase of horizontal components, vertical components, and resultant of the velocity between classes F52 and F55 were respectively 3.14 m/s, 2.95 m/s, and 3.91 m/s for the females and 1.11 m/s, 1.39 m/s, and 1.66 m/s for the males. The comparison of both genders in classes F52, F54, and F55 revealed that the velocity of release for the females was smaller than the males by 2.77 m/s, 2.15 m/s, and 0.74 m/s in the horizontal direction and 3.24 m/s, 0.76 m/s, and 1.68 m/s in the vertical direction. The resultant was respectively 3.71 m/s, 2.23 m/s, and 1.46 m/s less.

Position at Release (Figure 5)

The resultant of the position ranged from 2.01 m to 2.68 m, with a mean of 2.39 ± 0.26 m for the males and from 1.16 m to 1.98 m, with a mean of 1.70 ± 0.47 m, for the females. The athletes in the classes F52 men and F54 women released the shot before the origin of the GCS, while all the other athletes release it in front of the origin; however, the female F54 compensated by releasing the shot higher.

The comparison of both genders in classes F52, F54, and F55 revealed that the position of release for the females was 0.48 m, 0.92 m, and 0.10 m further back on the horizontal axis and traveled 1.32 m, 0.67 m, and 0.42 m less distance on the vertical axis than the males. The resultant was respectively 1.39 m, 0.71 m, and 0.43 m shorter.

Angle (Figure 6 and Table 2)

The increase of measured angle between classes F52 and F55 was 3.98° for the males and 16.55° for the females. The comparison of both genders in classes F52 and F55 revealed that the measured angle of the females was respectively 19.46° and 6.90° smaller than males, while the F54 was 3.78° higher.

The angle measured for the female athlete in class F54 was largely above the line of regression of the other female athletes; however, her angle was particularly close to the optimum angle, as reported in Table 2.
Calculated Performance vs. Classification

It can be noted that class F52 males performed 0.48 m more than subsequent class F53 (Figure 3). This might be due to the classification (functional differences) or to the fact that either the gold medalist in class F52 men performed particularly well for his classification or the athlete in class F53 under-performed.

Parameters of the Shot’s Trajectory

As expected, these results confirm the findings of previous studies focusing on elite and emerging able-bodied and stationary shot-putters (Bartonietz & Borgström, 1995; Chow et al., 2000; Frossard et al., 2003; Lichtenburg & Wills, 1978; McCoy et al., 1984; Zatsiorsky et al., 1981). The velocity and angle seem to be the two predominant factors determining the performance of gold medalists. The lack of strong relationship with the position at release might be explained by two hypotheses. The lying height, length of trunk, and throwing upper arm were similar for all the athletes and/or the difference in lying height was minimized since all the throwing frames have the same height of 75 cm, corresponding to the maximum height allowed by the IPC’s rule. This predetermined the position (height and advancement) at release. As explained further, more anthropometric data must be collected to validate these hypotheses. It is likely that the performance relied more importantly, however, on the throwing technique and functional outcome as they are both directly related to velocity and angle of release.

Parameters Across Classes

The relationship between the parameters of the shot’s trajectory and the performance or the classification should be interpreted with caution because only gold medalists

<table>
<thead>
<tr>
<th>Classes</th>
<th>F52</th>
<th>F53</th>
<th>F54</th>
<th>F55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured angle</td>
<td>28.49</td>
<td>27.54</td>
<td>30.73</td>
<td>32.47</td>
</tr>
<tr>
<td>Optimum angle</td>
<td>37.46</td>
<td>38.61</td>
<td>37.99</td>
<td>39.58</td>
</tr>
<tr>
<td>Angle difference</td>
<td>8.97</td>
<td>11.07</td>
<td>7.26</td>
<td>7.11</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured angle</td>
<td>9.02</td>
<td>-</td>
<td>34.52</td>
<td>25.57</td>
</tr>
<tr>
<td>Optimum angle</td>
<td>34.77</td>
<td>-</td>
<td>36.39</td>
<td>39.03</td>
</tr>
<tr>
<td>Angle difference</td>
<td>25.74</td>
<td>-</td>
<td>1.88</td>
<td>13.46</td>
</tr>
</tbody>
</table>
were included in this study and because of the lack of evidence of proportional distribution of classes. However, the velocity (Figure 4) and the measured angle (Figure 5) of the shot at instant of release increased with the performance and classification for both males and females. The position of the shot at release (Figure 6) revealed a similar trend but it was weaker, particularly for males. Consequently, the results tend to confirm that the athletes included in this study were classified fairly.

**Figure 4** — Horizontal and vertical components and the resultant of the speed of release of the shot for the male and female gold medalists in each class (from F52 to F55) during world-class events.
Parameters Across Gender

Females produced lower values than males do in all parameters. In fact, the magnitude of all the parameters was in most cases ranked from the F52 women to the F55 men with the F55 women overlapping the F52 men. This might be due to anthropometric and/or physiological discrepancies between genders, as far as speed-based activities are concerned. It should be noted that the differences between male and female athletes of the same class decrease linearly as the classification progresses.

From Descriptive to Comprehensive Biomechanical Analyses

This study is mainly descriptive and yet original, as the results provided benchmark parameters of the shot’s trajectory of elite male and female stationary throwers in consecutive classes during world-class events; however, it has three main limitations. Unfortunately, one of the trade-offs of recording during the actual event was that only one camera could be used, so the parameters were assessed only in the sagittal plane. This enabled determination of the parameters with sufficient accuracy for most attempts. As expected, however, the error was larger than that usually obtained in experimental conditions where several cameras can be used. In principle, the best way to alleviate this limitation is to use a three-dimensional motion analysis system. The actual trajectory of the shot could then be calculated in 3D rather than 2D, thereby increasing the accuracy of velocity and angular data. Ideally, at least four cameras aligned diagonally with each corner of the plate and preferably a fifth one located above the athlete would be required. While this camera arrangement is possible in an experimental framework, it is particularly difficult to implement in the field of play during a world-class event. It is also more likely...
that organizing committees would deny access to the field of play, judging this setup too invasive. In addition, it is highly likely that the field of view of cameras on the ground would become obstructed or moved during the course of the event, as up to 40 people work in the throwing area alone. A more realistic alternative would be to use two newly commercially available high-speed cameras recording

Figure 6 — Horizontal and vertical components and the resultant of the position of the shot at the instant of release for the male and female gold medalists in each class (from F52 to F55) during world-class events. A negative position on the horizontal axis indicates that the shot was released behind the GCS.
at least at 100 Hz with full resolution. These could be placed at a distance on the front and the side of the thrower, allowing a bi-planar analysis in the sagittal and frontal plane. In principle, it should also enable a 3D reconstruction.

This study focused on parameters of the shot’s trajectory, since they are the key determinants of the performance. However, results demonstrated a need for future studies focusing on the relationships between these parameters and the anthropometric profiles of the athletes. In addition, future comprehensive studies would benefit from a more complete biomechanical analysis, focusing on the sequence of actions prior to the release of the shot (Figure 1). This can include parameters such as the duration of the technical phases of the putting action and range of motion of each body segment, the linear and angular momentum taking into consideration the inertial characteristics of each segment and mechanical energy expended. All combined, this data should provide a better understanding of the throwing technique in terms of functional outcomes, coordination, and efficiency.

Finally, a total number of seven gold medalists were included. This group should be divided into two subsamples of four males and three females for a proper statistical analysis. Unfortunately, the small number of samples did not allow sufficient power for statistical analyses such as correlation tests and meaningful confidence intervals to be carried out. This limitation has dictated the descriptive nature of the study. The classification system is based on the functional potential continuum. Therefore, each class includes a range of functional potential. Thus, a single athlete, let alone the gold medalist, can hardly be representative of a given class. Consequently, future comprehensive analyses will require an intra-class analysis, including all the attempts of all athletes ranked from gold medalist to last in a given class and inter-class analysis, including the athletes in all the classes ranging from F52 to F58. This will provide a better insight into the correlation between functional outcomes, performance, and classification (McCann, 1993; Tweedy, 2002; Vanlandewijck & Chappel, 1996) and of the parameters optimized by the best athletes (Chow et al., 2000; Linthome, 2001).

**Conclusion**

This present study is the first attempt to report the parameters of a shot’s trajectory based on world-class event recordings of elite male and female stationary throwers in consecutive classes. The results confirm previous studies demonstrating that the velocity and the measured angle of the shot at the instant of release are the most important determining parameters for males and females. In addition, the study reported that females produced lower values than males did in all parameters, although the differences between male and female athletes of the same class decreased linearly as the classification progressed.

This descriptive study should be considered as a milestone for more comprehensive inter and intra-class analyses based on three-dimensional kinematic data of the sequence of actions prior to the release of the shot and the shot’s trajectory at the instant of release; however, it is anticipated that this study will provide some key benchmark information to all stakeholders (sports scientists, coaches, athletes, classifiers) of the stationary shot-put event who are facing the challenge of improving the performance of the athletes and the fairness of the event.
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