A Three-Dimensional Analysis of Finger and Bow String Movements During the Release in Archery

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The aim of this paper was to examine finger and bow string movements during archery by investigating a top Austrian athlete (FITA score = 1233) under laboratory conditions. Maximum lateral bow string deflection and angular displacements for index, third, and ring fingers between the full draw position and the end of the release were quantified using a motion tracking system. Stepwise multiple regression analyses were used to determine whether bow string deflection and finger movements are predictive for scoring. Joint ranges of motion during the shot itself were large in the proximal and distal interphalangeal joints, and much smaller in the metacarpophalangeal joints. Contrary to our expectations, greater deflection leads to higher scores ($R^2 = .18, p < .001$) and the distal interphalangeal joint of the third finger weakly predicts the deflection ($R^2 = .11, p < .014$). More variability in the joint angles of the third finger was found in bad shots than in good shots. Findings in this study let presume that maximum lateral bow string deflection does not adversely affect the archer’s performance.

Keywords: biomechanics; kinematics; motion analysis; performance; sport

Archery can be described as a static sport that requires strength and endurance of the upper body, particularly of the shoulder girdle and forearm muscles (Mann & Littke, 1989). High performance shooting in archery is characterized as the capability of hitting the target repeatedly in a certain amount of time with high precision and accuracy (Leroyer et al., 1993; Martin et al., 1990).

Olympic recurve archery technique can be described as follows (Edelmann-Nusser et al., 2006): The archer draws the bow by pulling the arrow tip toward the clicker, holds on in that position (full draw position) and aims. After that the archer pulls the arrow through the clicker and shoots. Other researchers describe the shot as a three phase movement: the stance, the arming and the sighting (Leroyer et al., 1993). Nishizono et al. (1987) further divided the shot in archery into six different phases: bow hold, drawing, full draw, aiming, release and follow through.

Because a voluntary arrow release decision could perturb the sighting phase, a simple device called a “clicker” has been established as a common piece of equipment. It consists of a flat spring with one end fixed at the window of the bow riser and the other resting on the arrow. When the final stance position is reached the clicker is released, producing a light sound which is the stimulus to extend or relax the fingers of the drawing arm and therefore induces the release of the bow string (Leroyer et al., 1993). Directly after releasing the arrow, changes in muscular activity of the shoulder and back are detectable (cf. Zipp et al., 1978; Zipp, 1979; Hennessy & Parker, 1990). From a biomechanical perspective, the archer must manage the release of the external bow tension and the muscular forces immediately after the shot by means of fine neuromuscular control (Edelmann-Nusser & Gollhofer, 1998). Simultaneously the archer has to aim, pull the arrow through the clicker and react on the clicker’s fall without disturbing the lateral deflection of the bow and bow string. Due to these facts, Edelmann-Nusser (2005) concludes that the sensor and motor process in archery is to be seen as very complex.

The archer is supposed to release the bow string accurately by coordinating small muscles (extensors and flexors) of his/her forearm. Each archer develops his/her own strategy of releasing the arrow. To investigate muscular activity and finger movement, several authors used surface EMG for analyzing muscular activity, muscular coordination and different types of release strategies during bow string release (Clarys et al., 1990; Ertan et al., 2003; Martin et al., 1990; Soylu et al., 2006).

Two main strategies have been found by Martin et al. (1990): the archer’s release of the bow string showed either a clear decline in muscular activity of the flexor muscles of the drawing arm before release or a distinct burst of extensor activity immediately before release.
Contrarily, Ertan et al. (2003) and Ertan (2009) found that all archers release the bow string by active contraction of the forearm extensors, a clear relaxation of the forearm flexors affecting the release movement was not observed.

Alternative non-EMG approaches can be found at Zipp et al. (1978) who used an accelerometer to investigate fingertip-acceleration of the third finger, or at Martin & Heise (1992) who quantified force distribution between the hand of the bow arm and the grip using unobtrusive force sensors.

High speed cinematography shows that the bow string slides off the fingers laterally as they relax. As a consequence, the bow string will have a lateral velocity at the instant that contact is lost with the fingers and will reach maximum some time later. It is suggested that an active extension of the releasing fingers is more likely to produce lateral deflection of the bow string and less consistent shot-to-shot performance (Martin et al., 1990).

Video-based or optoelectronic motion analysis have been used extensively in the field of motion and gait analysis. Optical tracking is a well-established technique for measurements of body kinematics and does not hinder the movement of the human body. It enables the measurement of body kinematics by tracking small reflective markers positioned on bony landmarks of the human body. The collected data from the reflective markers can be reconstructed and further used for three-dimensional analysis. In the past few years, motion analysis of finger and hand motion has gained large attention (e.g., Cerveri et al., 2007; Degeorges et al., 2005; Kuo et al., 2002; Rash et al., 1999; Veber et al., 2007 and Zhang et al., 2003). However, none of the investigations in archery have focused on the finger motion itself in its three-dimensional aspects. In particular, the ranges of motion for all fingers and joints for the three finger grip during the shot have been poorly investigated. A better understanding of the ranges of motion for the releasing fingers can presumably lead to more appropriate training and coaching in archery. Therefore, in the first part of this study, finger and joint kinematics of the releasing fingers were analyzed to establish ranges of motion during the shot for all participating finger joints.

Because of a common tenet in archery that lateral bow string deflection has a detrimental effect on archers’ performance, the second goal of this study was to determine the relationship between maximum lateral bow string deflections (D) and the motion of all participating finger joints within good and bad shots as well as archery performance itself.

**Method**

A motion tracking system (VICON Motion Systems Limited, Oxford, UK) was used to measure finger and bow string movements (Figure 1). The system consists of eight infrared cameras (six cameras with a resolution of

![Figure 1 — Camera positions (C1-C8) and global coordinate system.](image-url)
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1.3 megapixels, and two cameras with a resolution of 4.0 megapixels, an acquisition station system (VICON MX Net) connected to a personal computer, and 3D reconstruction software (VICON Nexus and BodyBuilder). Data were collected at 500 Hz. System accuracy was tested by tracking two markers mounted at a known distance on a rigid object. The range of marker distances yielding differences in length was less than 0.2 mm. Kinematic calculations were performed using the raw data.

The majority of competitive archers use the three-finger grip release (Clarys et al., 1990). The finger release is defined as the point at which the bow string slips off the first three finger tips. The movement analyzed in this paper was therefore predominantly of the index, third and ring finger.

Semicircular markers with a diameter of 9 mm were used and positioned on bony landmarks on the archer’s hand of the drawing arm. For investigating bow string movement a 4 mm cylindrical marker was placed on the bow string 7 cm below the nock point (Figure 2), the point which marks the attachment point of arrow and bow string.

A right hand model (VICON) was adapted, excluding thumb and little finger. The hand markers protocol consisted of 20 markers (Figure 2). Four markers represented the distal forearm (RFA1, RFA2, RWRA and RWRB), six the metacarpal area (RH1, RH2, RH3, RH4, RH5 and RH6), three the index finger (RIF1, RIF2 and RIF3), three the third finger (RTF1, RTF2 and RTF3) and four the ring finger (RRF1, RRF2, RRF3 and RRF4). Markers representing the distal forearm were placed on the medial aspect of the distal ulna and lateral aspect of the distal radius (RFA1, RFA2) and on the wrist bar of the thumb and little finger side (RWRA, RWRB). The metacarpal markers were placed on the dorsal aspect of the bases of the second and fifth metacarpal bones and on the metacarpophalangeal joints (MCP). The markers of the index, third and ring fingers were placed on the dorsal aspect of the proximal interphalanageal joints (PIP), distal interphalanageal joints (DIP) and the finger tips of each finger. Another marker was placed between the MCP and the PIP joints of the ring finger (RRF1). Furthermore, two virtual hand markers (RHNDV1, RHNDV2) were used to define segment axes of the hand. The local coordinate system of the hand was defined as follows (Figure 3): The point RHNDV1 was set as the origin. This point was determined by calculating the middle point of the vector between the points RH1 and RH6. The X’ axis was defined by calculating the vector between the points RH3 and RHNDV1. The cross product of X’ and the vector between the points RH6 and RH1 was calculated to define Z’. The cross product of Z’ and X’ defined Y’. Flexion/extension angles were calculated using the technique of Cheng & Pearcy (1999).

The investigated participant was a competitive archer from the Austrian B-National Team who took part in several national and international competitions (e.g., World Games 2007). The subject was 49 years old, and had six years of experience in competitive recurve archery. His best FITA Indoor and Outdoor competition scores were 1131 points out of 1200 and 1233 points out of 1400. Before participation, the subject read and signed a consent form, which was approved by the Institutional Review Board at the Centre for Sports Sciences and University

Figure 2 — Marker placement: bow string and hand.
Sports of the University of Vienna. The subject participated in three test sessions in the Biomechanics Laboratory at the University of Vienna. Each session consisted of ten sets of three shots at a distance of 18 m using a FITA Indoor 40 cm triple target face. In sum, ninety shots were captured out of which, due to marker occlusion, fifty-six shots could be used for further analysis.

For each shot, the range of motion of each finger joint (MCP, PIP, and DIP) between the instants of the full draw position and the end of the release were measured. Both instances were determined by defining a threshold for the velocity of the wrist of the drawing arm (by the RFA1 marker). As the wrist velocity decreased to 0.1 m/s in the full draw position, and after releasing the bow string in the follow through phase, the start and end of data acquisition was determined. The range of motion of each finger (FROM) was defined as the sum of ranges of motion of its three joints (JROM). The range of motion of each joint was then expressed as a percentage of the corresponding finger’s range of motion (PROM).

Maximum lateral bow string deflection D was calculated for every trial in the horizontal plane. First, the lateral bow string deflection was calculated for every frame between finger release and the release of the arrow from the bow string. For this calculation, the positions of the string marker at finger release, at release of the arrow from the bow string, and at the time of the frame, were projected onto the horizontal (XY) plane, producing points A, B, and C, respectively. Lateral bow string deflection for the frame then was calculated as the perpendicular distance from point C to the straight line joining points A and B. The maximum lateral bow string deflection, D, was the largest of these values.

All statistical analyses were performed using SPSS ver. 15.0 (SPSS Inc., Chicago, IL). Stepwise multiple regression analysis was used to test whether a model incorporating JROMs from all three fingers could predict the maximum deflection (D). The nine variables (i.e., ROMs of three fingers and three joints) were entered in the model at a significance level of \( p < .05 \) and removed from it at \( p > .10 \). The regression method was further conducted to determine predictor variables (ROMs, D) for the scores. Those scores represent the archery performance. A significance level of \( \alpha < .05 \) was used for all analyses. One outlier, defined at three standard deviations about the mean, was identified in D and eliminated.

**Results**

The ranges of motion of the MCP, PIP, and DIP joints (JROM values) were \( 9 \pm 2^\circ \), \( 30 \pm 2^\circ \) and \( 42 \pm 5^\circ \) for the index finger, \( 7 \pm 2^\circ \), \( 32 \pm 2^\circ \) and \( 19 \pm 2^\circ \) for the middle finger, and \( 6 \pm 2^\circ \), \( 15 \pm 2^\circ \) and \( 28 \pm 4^\circ \) for the ring finger. These values added up to combined ranges of motion (FROM values) of \( 81 \pm 5^\circ \) for the index finger, \( 58 \pm 3^\circ \) for the third finger, and \( 48 \pm 5^\circ \) for the ring finger. Both the PIP and DIP joints accounted for substantial percentages (PROM values) of the combined ranges of motion in the index, third and ring fingers (\( 37 \pm 3\% \), \( 55 \pm 4\% \) and \( 30 \))
Stepwise multiple regression analyses identified the DIP joint of the third finger as the single most important variable in predicting D and explained a weak but statistically significant 11% of the variance in deflection ($F = 6.508; R = -0.331; R^2 = .109; p = .014; SEE$ (standard error of the estimate) = 0.82). D itself was identified to explain 18% of the variance in scores ($F = 11.732; R = .426; R^2 = .181; p = .001; SEE = 0.718$).

**Discussion**

In this study, fifty-six shots of a competitive archer were analyzed in terms of finger joint kinematics and maximum lateral bow string deflection in the horizontal plane. A common and predominant tenet among athletes and coaches is that higher lateral bow string deflection has a detrimental effect on the archer’s shooting performance. The results in this paper do not support these assumptions. Multiple regression analysis revealed a weak but statistically significant positive relationship with maximum lateral bow string deflection and scores. These findings would suggest that minimizing lateral bow string deflection is not such a crucial issue in the expert archer’s performance.

**Table 1** Range of motion for the index, third and ring fingers and the MCP, PIP and DIP joints

<table>
<thead>
<tr>
<th></th>
<th>FROM [°]</th>
<th>JROM [°]</th>
<th>PROM [%]</th>
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<tbody>
<tr>
<td></td>
<td>MCP</td>
<td>PIP</td>
<td>DIP</td>
</tr>
<tr>
<td>Index finger</td>
<td>9 ± 2</td>
<td>30 ± 2</td>
<td>42 ± 5</td>
</tr>
<tr>
<td>Third finger</td>
<td>7 ± 2</td>
<td>32 ± 2</td>
<td>19 ± 2</td>
</tr>
<tr>
<td>Ring finger</td>
<td>6 ± 2</td>
<td>15 ± 2</td>
<td>28 ± 4</td>
</tr>
<tr>
<td></td>
<td>MCP</td>
<td>PIP</td>
<td>DIP</td>
</tr>
<tr>
<td>Index finger</td>
<td>11 ± 2</td>
<td>37 ± 3</td>
<td>52 ± 6</td>
</tr>
<tr>
<td>Third finger</td>
<td>12 ± 3</td>
<td>55 ± 4</td>
<td>33 ± 4</td>
</tr>
<tr>
<td>Ring finger</td>
<td>13 ± 3</td>
<td>30 ± 5</td>
<td>57 ± 9</td>
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Because of the phenomenon that the arrow is snaking around the grip of the bow, also known as the Archer’s paradox (Kooi & Sparenberg, 1997; Zanevskyy, 2001), there always must be D, but an interindividual optimum level of D could exist which presumably is not zero.

Although there is evidence that the range of motion of the DIP joint accounts for partial variance in maximum lateral string deflection D, it is possible that D is not a consequence of finger release, but rather of small differences in arrow stiffness. Lateral deflection variation could also be affected by slight differences in movements of the bow arm (and therefore of the bow) immediately after the release from the drawing arm. For example, if in one shot the string-path deflects further toward the right, this will tend to make the final segment of the string-path have a direction more toward the left as the arrow leaves the string. By itself, this would probably make the arrow hit the target farther to the left. But if, in addition, the archer’s bow arm was placed slightly farther to the right relative to the drawing arm, this would compensate for the effect of the smaller string deflection. As a result, the arrow would end up in the same position on the target as a previous shot that had less string deflection.

As there are only a few milliseconds between the bow string release from the drawing arm and the arrow release from the bow string, there is no means of open loop control. If the archer’s bow arm fails to come to rest before the bow string release, one would expect poorer reliability and accuracy.

A limitation of the study is that there are no data exploring the arrow alignment to the target and its relation to the bow throughout its trajectory. Even though this could pose some formidable technical difficulties, it would be of considerable interest and a point for further research.

As a consequence of the unexpected results, additional analyses were performed. The time scales of the third finger joints of three randomly selected shots out of “good shots” with scores of 10 and three randomly selected shots out of “bad shots” with scores of 8 have been adjusted making the negative peaks of the PIP joint coincide. The results are plotted as examples in a time range shortly before and after the peak of the PIP joint in Figure 4.

As it can be seen the peak-minimum values in both groups are quite similar for all three shots, and the characteristics of the graph before and after their minimum peak shows hardly any differences for the “good shots” but clearly more differences for the “bad shots”. For a more detailed quantification of this difference in variability, two groups of shots were formed for statistical analysis: a good group (score of 10 or $x$; $x$ is the innermost score area of the target face; $n = 12$) and a bad group (score of 8 or less; $n = 18$) (cf. Keast & Elliot, 1990). Means and standard deviations of the adjusted time curves of all good and bad shots were calculated for the third finger joints within a reasonable time range (0.05 s before and 0.025 s after the negative peak of the PIP joint with a sampling rate of 500 Hz, therefore $n = 37$, see Figure 5).
Figure 4 — Variability in the third finger joint angles of randomly selected shots: (a) Three out of “good shots.” (b) Three out of “bad shots.”
Figure 5 — Time-adjusted mean third finger joint curves of good (black) and bad shots (gray): a) MCP, (b) PIP, (c) DIP. Error bars for good shots (black) represent +1 SD. Error bars for bad shots (gray) represent -1 SD.
Figure 6 — Spatiotemporal resolution of the bow string deflection in XY-plane. Further, the figure shows a representative graph of a PIP joint curve illustrating where the bowstring release from the fingers occurs.
Summary measures were used to analyze the variability in the joint angles (cf. Matthews et al., 1990): for each shot the absolute area between the time curve and the overall mean of the group was calculated. Both groups were compared using t-tests for independent variables; statistical significance level was set at p < .05. The results showed significant differences in the MCP joint ($t = -2.978; p = .006$) but not in the PIP ($t = -1.593; p = .122$) and the DIP joints ($t = -0.614; p = .545$).

These findings support the assumption of Edelmann-Nusser (2005) that in highly skilled athletes the neuromotor control program of arrow release in the manner of an Open Loop-movement already is initiated before the clicker’s fall. The observed systematic differences in variance between “good” and “bad shots” support this assumption. An alternative interpretation could be that the mechanism is purely mechanical instead of neuromotor. For example, the archer might have great inconsistencies in the early phase of drawing or aiming. But we suggest that such assumptions can be neglected because the small number of shots with mechanical difficulties will normally be aborted by elite archers.

This underlines the importance of the reproducibility of the archer’s release and shooting technique. If the archer is able to reproduce the same movement pattern each time and therefore the same motor program, there is a higher likelihood of performing a good shot. Heller et al. (2004) support this assumption: in a longitudinal analysis of the surface EMG characteristics of the trapezius pars transversa using time-variant spectral analysis they identified two main strategies of muscular activity immediately before the contact-loss of the arrow with the bowstring. According to literature (e.g., Edelmann-Nusser & Gollhofer, 1998), for ten out of twelve archers a decreasing rectified smooth EMG and mean power could be found. For the other two archers, the activity increased. These two observations were not only typical for one test session but for all five test sessions within the two years of observation and for each archer.

Because this study represents fundamental research in three-dimensional analysis of finger movement in archery, only one participant was investigated. For that reason the results cannot be generalized and the need to reproduce this research with a greater number of subjects is highlighted. Another factor which could have an effect on the findings is that the participant reported an old trauma of his third finger DIP joint. Even though he reported no further problems, it has to be taken into account that this trauma could possibly have an effect on the kinematic behavior of his DIP joint.

A VICON motion tracking system, which provides a maximum sampling rate of 500 Hz, was used for analysis. Although this is a relatively high sampling rate in the field of human motion analysis, it seemed to be critical in temporal resolution, especially for tracking the bow string motion. At the instant of bow string release and during the following bow string acceleration, the spatio-temporal resolution decreases rapidly (Figure 6). A higher sampling rate would be desirable for further analyses.

A measuring setup for three-dimensional motion analysis of the hand and bow string motion in archery was developed. Ranges of motion for all interacting finger joints were displayed and values indicate greatest involvement of the PIP and DIP joints. Findings in this study do not support the common tenet in archery that maximum lateral bowstring deflection adversely affects archer’s performance. Rather, it is suggested that the archer’s ability to reproduce the same movement pattern each time increases the likelihood of performing higher scores. These findings should be further investigated with a greater number of subjects.

References


