ZHANG, Baifa and LIN, Zhi-Cheng. A Comparative Study on the Joint Coordination of Archery Athletes of Different Skill Levels: Based on Functional Data Analysis. Quality in Sport. 2024;36:56307. eISSN 2450-3118.
https://dx.doi.org/10.12775/QS.2024.36.56307
https://apcz.umk.pl/QS/article/view/56307

The journal has been 20 points in the Ministry of Higher Education and Science of Poland parametric evaluation. Annex to the announcement of the Minister of Higher Education and Science of 05.01.2024. No. 32553.
Has a Journal's Unique Identifier: 201398. Scientific disciplines assigned: Economics and finance (Field of social sciences); Management and Quality Sciences (Field of social sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 r. Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398.
Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 22.11.2024. Revised: 19.12.2024. Accepted: 20.12.2024. Published: 20.12.2024.

A Comparative Study on the Joint Coordination of Archery Athletes of Different Skill Levels: Based on Functional Data Analysis

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Abstract
Purpose: Joint coordination is a critical factor influencing high-quality technical movements. By analyzing the changes between joints through functional data analysis, characteristic parameters can be derived. This study employs functional data analysis to explore the differences in joint coordination characteristics among archery athletes at various skill levels, offering a new perspective for coaches and athletes to analyze specific movement techniques.
Methods: Twenty-eight archery athletes were selected as subjects, including eight international master athletes, twelve national first-level athletes, and eight national second-level athletes from Chinese national and province team. An infrared light spot motion capture system was utilized to gather kinematic parameters during the archery shooting process. Functional data analysis was employed to determine the upper limb joint coordination characteristic parameters of athletes at different skill levels.
Results: Archery athletes at different levels exhibit three types of joint coordination characteristics between the shoulder and elbow joints during the drawing and aiming phases. The first type of joint coordination characteristic shows statistical differences across levels (P=0.03). These differences are primarily due to the following: 1) For international master athletes, the movement speeds of the shoulder and elbow joints both peak in the early phase of drawing; 2) The range of coupled motion between the shoulder and elbow joints is higher in the early phase of drawing and lower in the latter half, and consistently lower during the aiming phase; 3) The duration of the drawing phase is shorter.
Conclusion: Functional data analysis effectively captures the differences in upper limb joint coordination characteristics among archery athletes at various levels. Superior athletes typically exhibit synchronous shoulder-elbow joint movements, enhanced feedforward capabilities, and a quicker rhythm of movement.
Keywords: Functional Data Analysis; Joint Coordination; Archery;

1. Introduction

Archery, a skill-based sport, incorporates both dynamic and static movements across four technical stages: bow lifting, drawing, aiming, and follow-through. These stages require high technical proficiency from athletes （Spratford et al., 2017）. Particularly critical are the drawing and aiming phases, during which the appropriate shoulder and elbow joint angles on the bow-drawing side critically influence the force line in pushing and pulling the bow（Ganjave et al., 2021）. This alignment directly affects the quality of the release action and the arrow's final landing point （Simsek et al., 2014）. Research often highlights the postural angles of the upper limb joints at characteristic moments as key indicators of archery technique; however, the coordination between adjacent joints is rarely discussed（Vendrame et al., 2022）. Such coordination represents the ability to maintain appropriate relationships between joints, reflecting the central nervous system's control over biomechanical degrees of freedom in terms of timing information （Baifa et al., 2023）. Studies in sports like ice hockey（Brétigny et al., 2008）, skating（Khuyagbaatar et al., 2017）, fencing（Mulloy et al., 2018）, and gymnastics（Hiley et al., 2019）show that high-level athletes typically exhibit more refined joint coordination characteristics. Furthermore, joint coordination characteristics correlate with performance levels among archery athletes（Serrien et al., 2018）, suggesting that identifying variations in joint coordination among athletes at different performance levels could provide crucial insights for enhancing athletic performance.

In practice, joint coordination characteristics are described by the degree of similarity between joint movements, or the coupling relationships between joints. This is visually presented through joint angle diagrams and quantitatively analyzed using methods like the vector coding and the continuous relative phase（Irwin et al., 2020）. However, the quantification results from these methods often lack sensitivity and are difficult to interpret in terms of real physical meanings. To overcome these limitations, scholars have introduced Functional Data Analysis (FDA), a novel mathematical tool（Leroy et al., 2018）. FDA, a testing method for random curves, transforms discrete observational data into smooth function curves. It employs dimension reduction algorithms to effectively extract implicit differences between these curves. This method has been proven to accurately capture changes in joint coordination characteristics throughout the complete movement process. Moreover, FDA's analytical results retain the initial units, simplifying the linkage of joint coordination characteristics to their real physical meanings（Warmenhoven et al., 2019a ; Warmenhoven et al., 2019b）.

Therefore, this study employs functional data analysis to examine the differences in upper limb joint coordination characteristics among archery athletes at various performance levels during the drawing and aiming phases. By exploring these joint coordination characteristics from a motion control perspective, the study aims to provide theoretical support for the scientific training of high-level archery athletes' specialized techniques.

1 Methods

1.1 Participants

This study selected participants from the Chinese national team who trained between 2018 and 2020 in preparation for the 2020 Tokyo Olympics, including all team members (8 international master athletes). Additionally, 20 athletes from Chinese provincial teams were included (12 national first-level athletes and 8 national second-level athletes). All subjects were left-handed archers, meaning the left arm was used for holding the bow and the right arm for drawing. None of the participants had sustained upper limb injuries in the six months prior to testing.

Table 1 Means and standard deviations of age, weight, height, drawing weight and archery experience of the subjects.

Groups	Age	Heights (cm)	Weights (kg)	Drawing weights (lb)	Archery experience (year)
International master level (n=8)	19.6±3.8	175.1±7.6	77.6±9.1	46.3±4.8	4.9±2.0
National first level (n=12)	17.4±1.3	174.4±6.8	72.9±12.3	42.1±5.2	3.5±1.9
National second level (n=8)	16.0±1.3	175.0±10.1	72.1±13.7	42.3±4.2	2.2±0.8

1.2 Instruments

An 8-camera infrared high-speed motion capture system (Qualisys, Sweden, 200Hz) was used to collect kinematic data of the archers' movements. Additionally, a high-speed motion camera (Qualisys, Sweden, 100Hz) was utilized to simultaneously capture video from the side to determine the moment of the archers' release.

1.3 Experimental Protocol

The test environment was a regular indoor training facility. Before the test began, basic information about the subjects was recorded. After being informed about the test procedure, subjects warmed up for 5 minutes wearing the same model of tight-fitting clothes. After warming up, a professional tester, using the upper limb model established by Rab（Rab et al., 2002）, attached 18 reflective markers (top of the head, seventh cervical vertebra, sternum, sacrum, both ear points, both acromion points, both coracoid processes, both radial styloids, both ulnar styloids, both third metacarpophalangeal joints, both anterior superior iliac spines) to the subjects. Additionally, three reflective markers were placed on the subjects' bows: above, below, and in front of the bow. The subjects then prepared in the testing area, and upon hearing the command, completed the archery motion test. The target was 30 meters away from the subjects. Coaches provided immediate feedback on the quality of each archery action. During the official test, each subject provided 12 valid data sets, resulting in a total of 336 valid data sets from 28 participants. Valid data are defined as those where the motion quality met the coaches' criteria and biomechanical parameters were fully captured.

1.4 Data Analysis

This study, integrating previous literature（Soylu et al., 2006 ; Ertan et al., 2005） and the displacement characteristics of the bow and string, identified three characteristic moments in archery and divided them into two action phases. The Drawing Phase begins at the moment of bow drawing, defined as the point when the front of the bow reaches its highest vertical position, and ends at the bracing moment. The bracing moment is defined as the first frame in which the lateral point of the right elbow joint has a displacement of less than 0.5mm for at least five consecutive frames in the anterior-posterior direction. The Aiming Phase starts at the bracing moment and ends at the release moment. The release moment is determined by high-speed video synchronized with the action, defined as the moment when the arrow leaves the string.

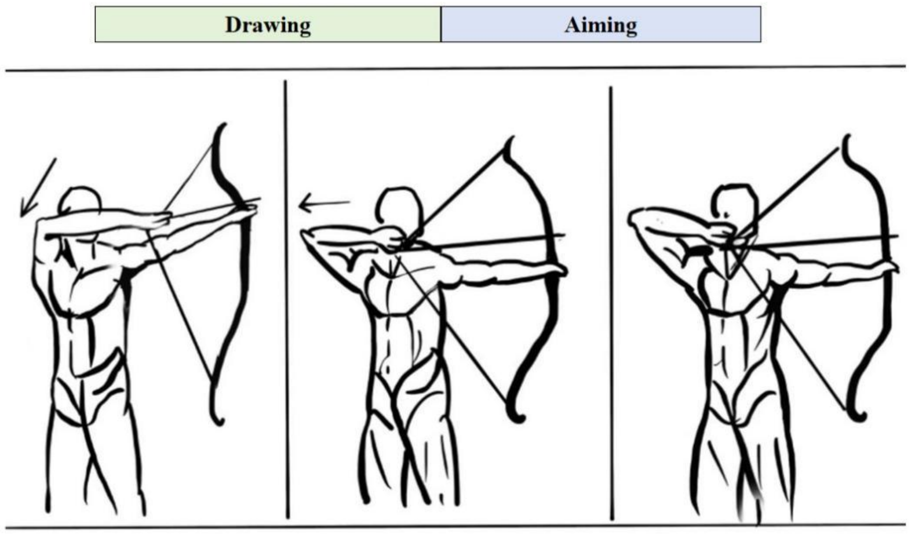

Figure 1. Illustration of a shooting cycle in an archer.

Kinematic parameters are computed using Visual 3D software. An upper limb multi-rigid body model is established based on the coordinates of the markers, and the three-dimensional angles of the upper limb joints are calculated using Euler angles. Functional Data Analysis is implemented on the Matlab R2015b platform using the FDA's Functional Principal Component Analysis (FPCA) toolkit（Ramsay, 2013）. The sagittal plane angles of the shoulder and elbow joints on the bow-drawing side are standardized, with the length set to 100. Since archery motion is non-periodic, 101 fourth-order B-spline bases are used to fit the time series curves of the upper limb joint angles into functional time series（Donoghue et al., 2008）. The optimal value for the smoothing parameter is determined to be -1.5 based on the Generalized Cross Validation (GCV) method. The mean function is estimated using the mean of the functional time series, as follows:

$$\hat{\mu} = \frac{1}{T}\sum_{t=1}^{T} f_t \#(1)$$

To compute the sample covariance function $\widehat{C}(s,\delta)$,where s and δ are independent variables.

$$\widehat{C}(s,\delta) = T^{-1}\sum_{t=1}^{T} f_t(s)f_t(\delta) \#(2)$$

$$\int \widehat{C}(s,\delta)\xi(\delta)d\delta = \hat{\lambda}\hat{\xi}(s) \#(3)$$

Subsequently, the principal component functions (ξ_k), corresponding eigenvalues (λ_k) , and principal component scores $(\widehat{\beta}_{t,\mathrm{k}})$—which represent the loading of the t$^{\mathrm{th}}$ sample f_t on the k$^{\mathrm{th}}$ principal component $\hat{\xi}_k$.

$$\widehat{\beta}_{t,k} = \langle \hat{\xi}_k, f_t - \hat{\mu}\rangle, k = 1,2,\cdots \#(4)$$

The criteria for determining the principal components are that the cumulative contribution rate reaches 90%（Ryan et al., 2006）and each principal component's eigenvalue is greater than 1. To facilitate the interpretation of the principal components, the varimax rotation method（Jolliffe, 2002）is used to enhance the interpretability of the results.

1.5 Statistical Analysis

One-way analysis of variance (ANOVA) is used to determine the differences in timing parameters of archery actions and joint coordination characteristics among athletes at different performance levels. The Least Significant Difference (LSD) method is employed for post-hoc testing, with the significance level set at $\alpha = 0.05$. Data analysis is conducted using SPSS 20.0 software.

2 Results

2.1 Timing Parameters

Statistical test results (Table 2) show that there are significant differences in the duration of the drawing phase among archery athletes at different performance levels ($P<0.01$). Subsequent LSD tests indicate that, compared to national second-level athletes, international master athletes and national first-level athletes have a significantly shorter duration in the drawing phase ($P<0.01$; $P<0.01$). There are no statistically significant differences in other indicators among archery athletes at different performance levels.

Table 2. Temporal characteristics of archery phases across different levels

	Phase	International Master Level	National First Level	National Second Level
Time（s）	Drawing	2.1±0.4♠	2.2±0.5♠	2.5±0.8
	Aiming	2.2±1.3	2.4±1.7	2.3±1.6
	Total Duration	4.3±1.3	4.6±1.7	4.8±1.8
Percentage（%）	Drawing	48.8±14.5	47.8±19.7	58.6±22.9
	Aiming	51.2±14.5	52.2±14.6	41.4±22.

2.2 Joint Coordination Characteristics

This study employed the FDA method to perform dimension reduction on the shoulder-elbow joint angle coupling curves during the archery process of subjects at different performance levels. The results identified three functional principal components that reflect joint coordination characteristics (Figures 2-4), explaining 90.7% of the total variance, with individual functional principal components accounting for 60.0%, 19.2%, and 11.5% of the variance, respectively. In the figures, part b represents the coordinate points of the shoulder-elbow joint angle coupling curves with the trajectory's upper left corner as the starting point of the archery action cycle and the lower right corner as the end. The blue arrows indicate the load vectors of the functional principal components, i.e., the vector sum of the two joint weight functions, reflecting the position and magnitude of differences between the shoulder-elbow joint angle coupling curves. When the load vector overlaps with the joint coupling curve, it indicates that the functional principal component primarily reflects phase variations between the curves. When the load vector aligns with the trajectory direction of the joint coupling curve, a higher positive load of this functional principal component suggests a faster speed of joint coupling movement, and vice versa. When the load vector does not overlap with the joint coupling curve and points towards a specific axis, such as the direction of shoulder joint movement, then the functional principal component primarily reflects the amplitude variation of the shoulder joint movement. Parts a and d of the figures show the solid lines of the mean joint angle change curves; the "+" curves represent the addition of the weight function to the mean, and the "-" curves represent the subtraction of the weight function from the mean. The area enclosed by the "+" and "-" curves indicates the location and size of variations. When the load is positive, the joint angle change curve is closer to the "+" curve, and vice versa for a negative load.

Table3 Variance explained by functional principal components

Functional Principal Component	Total Explained Variance (%)	Shoulder (%)	Elbow (%)
Functional Principal Component I	60.0	13.7	46.3
Functional Principal Component II	19.2	12.6	6.6
Functional Principal Component III	11.5	6.6	4.9

Functional Principal Component I explain 60% of the variance between curves, with the shoulder and elbow joints accounting for 13.7% and 46.3% of the total variance, respectively (Table 4). In the coordination characteristics described by this principal component, subjects with a positive load have a smaller range of coupled movement in the early half of the drawing phase and a larger range of coupled movement in the latter half of the drawing phase and throughout the aiming phase, while it is the opposite for subjects with a negative load. Statistical test results show that the level of athletic performance has a significant impact on the loads of Functional Principal Component I (P = 0.03). Subsequent LSD tests indicate that, compared to national first-level and second-level athletes, international master-level athletes have smaller loads for Functional Principal Component I (P = 0.04, P = 0.03).

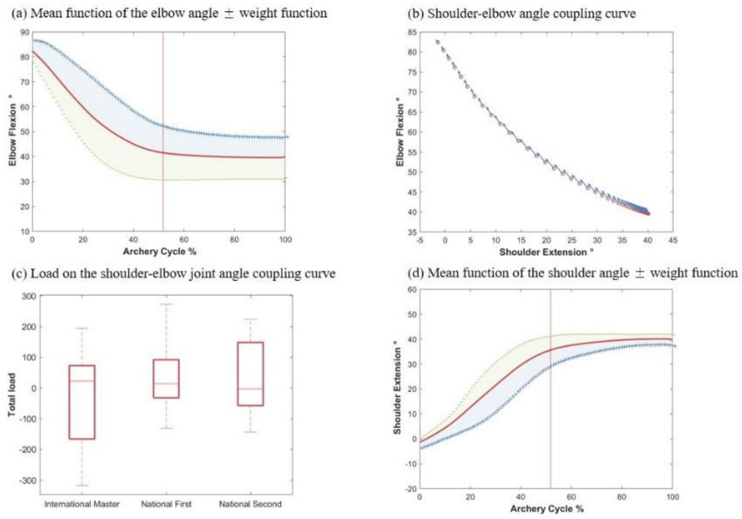

Figure 2. Functional principal component I

Functional Principal Component II explains 19.2% of the total variance, with the shoulder and elbow joints individually accounting for 12.6% and 6.6% of the total variance, respectively (Table 4). In the coordination characteristics described by this principal component, subjects with a positive load exhibit a larger range of shoulder-elbow joint coupling movement in the early half of the drawing phase, a smaller range in the latter half of the drawing phase, and a smaller range throughout the aiming phase. Conversely, subjects with a negative load show opposite characteristics. Statistical test results indicate that athletic level does not have a significant impact on the loads of Functional Principal Component II (Table 4).

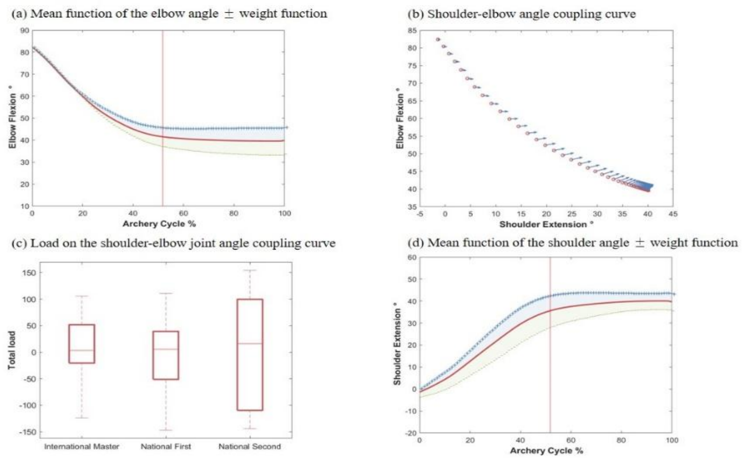

Figure 3. Functional principal component II

Functional Principal Component III explains 11.5% of the total variance, with the shoulder and elbow joints individually accounting for 6.6% and 4.9% of the total variance, respectively (Table 4). In the coordination characteristics described by this principal component, subjects with a positive load exhibit a smaller range of shoulder-elbow joint coupling movement in the early half of the drawing phase, a larger range in the latter half of the drawing phase, and a smaller range throughout the aiming phase. Conversely, subjects with a negative load show opposite characteristics. Statistical test results indicate that athletic level does not have a significant impact on the loads of Functional Principal Component III (Table 4).

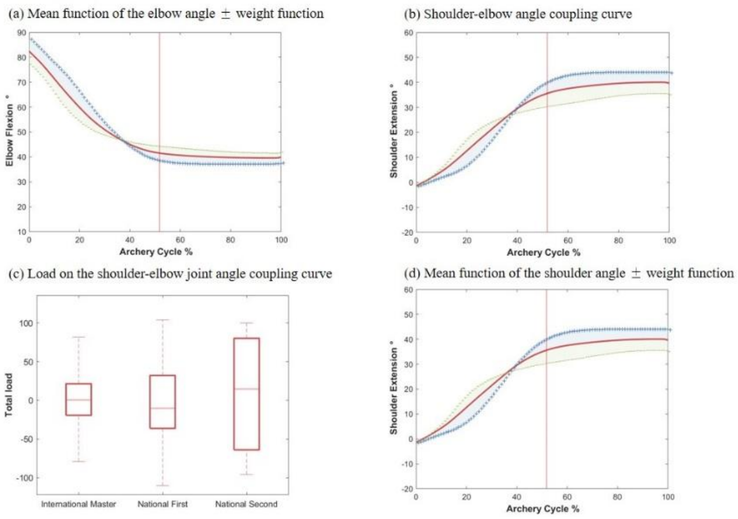

Figure 4. Functional principal component III

Table 4. Loads of functional principal components

Functional Principal Component	International Master Level	National First Level	National Second Level
Functional Principal Component I	-20.8±130.2♠♥	2.9±122.5	26.2±110.5
Functional Principal Component II	2.5±61.0	-3.1±63.8	5.0±97.1
Functional Principal Component III	6.3±50.1	-6.3±51.1	8.1±66.4

Note: Following the LSD tests, comparisons with national second-level athletes are indicated by ♠ for $P < 0.05$, and comparisons with national first-level athletes are indicated by ♥ for $P < 0.05$

4 Discussion

In archery, appropriate joint coordination characteristics are an essential component of high-quality technical actions. As motor skills mature, the technical movements exhibit more efficient coordination relationships. This study employed FDA technology to perform dimension reduction on the shoulder-elbow joint angle coupling curves on the bow-drawing side of archery athletes at different levels and to analyze these curves to explore reasonable joint coordination characteristics and discuss the applicability of this method in technical diagnostics. The results of this study indicate that after FDA processing, three functional principal components describing joint coordination characteristics were identified from the shoulder-elbow joint angle coupling curves on the bow-drawing side, with the first type of joint coordination characteristic being influenced by the level of athletic performance.

Changes in adjacent limb segments (joints) during human movement are not independent but are coordinated as a whole, presenting specific coupling relationships (coordination characteristics) to meet the demands of the movement task (Wheat et al., 2006 ; Bernstein, 1967). Hudson et al. (Hamill et al., 2006) believe that human segment coordination exhibits two characteristics: a sequential nature where segment motion speeds reach their peak from proximal to distal, and a synchronous nature where the speeds of all segments peak simultaneously. Joint coordination tends to be synchronous when high precision in technical actions is required and sequential when higher movement speeds are pursued. The results for Functional Principal Component I show that for international master-level athletes, the movement speeds (curve slopes) of the shoulder and elbow joints peak in the early half of the bow-drawing phase, whereas other levels of athletes reach peak speeds in the early and later halves of the bow-drawing phase, suggesting that superior athletes tend to have synchronous shoulder-elbow joint coordination. This is likely because athletes commonly believe that "faster rhythms lead to better performance" during daily training, with athletes at other levels pursuing a distinct fast rhythm during the bow-drawing phase, i.e., a tendency towards sequential coordination. The aiming task in archery does not start only after bracing but begins during the bow-drawing process, hence superior athletes maintain a fast rhythm while also focusing on the aiming task, i.e., joint coordination tends towards synchronicity. Moreover, Bernstein's theory of movement coordination (Latash, 2008) posits that the human body adjusts the coordination relationships between segments in advance before undertaking a new movement task to ensure that the target movement task is not adversely affected by prior coordination relationships that are unfavorable to the task, thereby improving movement quality and ensuring postural stability, i.e., through a "preset" feedforward adjustment mechanism. The results for Functional Principal Component I suggest that compared to other levels, international master-level athletes have a higher range of shoulder-elbow joint coupling movement in the early half of the bow-drawing phase and a lower range throughout the sighting phase and the latter half of the bow-drawing phase, indicating that superior athletes trigger feedforward adjustments entering the latter half of the bow-drawing phase, helping athletes transition efficiently from dynamic bow-drawing techniques to static sighting techniques and maintain stability during the sighting phase. Kisik Lee, the head coach of the Korean archery team, believes that the bow-drawing phase should be divided into two segments, with the end of the bow-drawing phase being a "load transfer segment," essentially the athlete gradually transferring the load from the arms to the back, externally manifested by a noticeable reduction in motion amplitude and speed. Superior athletes can initiate this segment earlier, which is crucial for smoothly transitioning to the sighting phase (USAA, 2013), and his training philosophy can be explained by the results of this study. Previous research has found that the rhythm of the bow-drawing phase influences archery performance, with superior archers characterized by short durations and fast rhythms, and the results of the bow-drawing phase time in this study are consistent with previous findings. The theory of movement rhythm (Scholz et al., 2000) suggests that athletes with better feedforward adjustment capabilities can effectively adjust their movement rhythm based on prior movement experiences. The timing of each phase of the archery action is an external manifestation of the action characteristics; the results of this study suggest that the fast rhythm of superior archers during the bow-drawing phase is based on strong feedforward adjustment capabilities and does not need to be overly emphasized in daily training. Additionally, the coordination characteristics described by the other two functional principal components show that the elbow joint movement trend during the bow-drawing phase is close to the average level, hence primarily dominated by shoulder joint movement. The higher the range of shoulder joint movement during this period, the lower the range of shoulder-elbow coupled movement during the sighting phase, and the higher the quality of the sighting action, with no statistical differences found in the loads of the above functional principal components among athletes at different levels.

5 Conclusion

Through functional data analysis, this study identified differences in joint coordination characteristics during the drawing and aiming phases among archery athletes at different levels. International master-level athletes tend to have synchronous shoulder-elbow coordination on the bow-drawing side, stronger feedforward adjustment capabilities, and a faster movement rhythm. It is recommended that future efforts focus on improving the synchronicity of the shoulder-elbow joints on the bow-drawing side during the early half of the drawing phase, and emphasize the "load transfer segment" in the latter half of the drawing phase as a breakthrough to enhance movement quality and improve athletic performance.

6 Author's contributions

B-FZ designed the study and wrote the manuscript; Z-CL searched for literature.

7 Funding

This work was supported by special fund project for basic research business expenses of the central universities of Southwest University in China (grant number SWU2309726).

8 Institutional Review Board Statement

The study was conducted in accordance with the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Beijing Sport University (protocol code 2020135H and approval date November 3, 2020). The study involved human participants, and informed consent was obtained from all subjects prior to participation.

9 Acknowledgments

We would like to thank staff and faculty at the school of sports at Southwest University.

10 Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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