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Effects of rifle handling length and supporting length on aiming performance and biomechanics

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Purpose: One of the most crucial factors affecting shooting performance is aiming stability, which is affected by the human–gun parameters. The effect of human–gun parameters on performance and biomechanics has not been investigated due to experimental limitations. This paper analyzed the aiming stability and biomechanics under different rifle handling length and supporting length based on experiments and musculoskeletal model. *Methods*: The aiming performance and balance posture with various rifle handling length and supporting length was obtained by the motion capture system. The artificial neural network was established to map the handling length and supporting length to the body balance posture. The human-gun musculoskeletal model calculated the joint reaction forces and muscle activation with different balance postures. *Results*: The effect of handling length and supporting length on aiming stability and biomechanics was analyzed. The muscle activation pattern was identified, and it could explain 83.8–98.2% of the variance in aiming stability. *Conclusions*: The outcomes of this study could find the most suitable human-gun parameters for shooters to improve performance and reduce the risk of musculoskeletal injury.

Key words: *aiming stability, rifle parameters, musculoskeletal model, muscle activation*

1. Introduction

For hand-held shooting rifles, in addition to the structure design of the rifle, which affects the shooting accuracy, the shooter's behavioral performance is also important. Postural stability and aiming stability of shooter's behavioral performance during the one-second aiming phase prior to firing are the two most important factors affecting shooting performance, accounting for 53 and 75% of the variance in shooting accuracy [21], [29]. The aiming stability is significantly correlated with shooting accuracy [2], [6], [32], and the postural stability is related to the shooting accuracy both directly and indirectly through rifle stability [1], [13], [19], [22]. Therefore, it is necessary to study the effect of human–gun parameters on aiming stability for rifle ergonomics design.

For free-standing shooting, the different human-gun parameters such as handing length (i.e., the length from trigger to stock), stock axis height, and supporting length (i.e., the length from trigger to support position) lead to changes in body balance posture. The body posture, the weight and weight distribution of the rifle change the joint reaction forces and muscle activation, thereby affecting aiming stability. Experimental study found that a rifle design with shorter handling length and lighter weight reduced the muscle exertion level and improved the aiming stability [32]. The effect of handling length on aiming stability is consistent with the shooting accuracy in the live fire study [16], [18]. Previous studies have investigated the biomechanical characteristics of rifle usage, with Selinger [25] examining the influence of rifle weight and weight distribution on upper extremity muscular fatigue, Coleman [4] investigating the impact of changes

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in rifle center of mass on rifle acceleration, Viboch [28] analyzing the effect of standing and kneeling posture on muscle activation, and Stone [26] researching the influence of the buttstocked and buttstockless structures on body's center of pressure.

However, the experimental test cannot measure the joint reaction forces using a non-invasive method. The subsequent research mainly established the human–gun musculoskeletal model using LifeMod/ADAMS [3], [14], [20] and AnyBody Modeling System (AnyBody Technology A/S, Aalborg, Denmark) [30, 31] to obtain the joint reaction forces and muscle activation during shooting. From the above, the experimental test method requires a large amount of data to study the effects of a few design parameters on limited muscles and aiming stability. Besides, the existing human–gun musculoskeletal models all analyze the firing impact on human body without giving consideration to the influence of human–gun parameters. The effects of human–gun parameters on aiming stability, musculoskeletal biomechanics, and muscle activation pattern have not been systematically studied, and aiming stability cannot be predicted.

The aim of this study was to analyze shooter's performance, musculoskeletal biomechanics and muscle activation pattern under different rifle handling length and supporting length. An artificial neural network was used to map the human–gun parameters to the body balance posture obtained by motion capture system. The human–gun musculoskeletal model with different balance postures was developed to calculate the joint reaction forces and muscle activation. The muscle activation pattern of the aiming process was described, and an attempt was made to estimate aiming stability. We hypothesized that the muscle activation pattern has the potential to explain the aiming stability under different handling length and supporting length. This method provided guidance for shooters to adjust the human–gun parameters to improve their performance and reduce musculoskeletal injury.

2. Materials and methods

The method of this paper is displayed in Fig. 1. The three directions of aiming stability and musculoskeletal model are shown.

2.1. Participants

Sixteen right-handed elite-level shooters (14 male and 2 female, age: 27 ± 2.3 years; height: 1.75 ± 0.25 m; weight: 70 ± 5.3 kg) without neurological or physical disease volunteered to participate in the study. All participants provided written informed consent, and the study was approved by the Research Ethics Committee of the researcher's institution. All methods were performed in line with the ethical principles of Declaration of Helsinki and approved by the ethical committee of the First Affiliated Hospital of Nanjing Medical University.

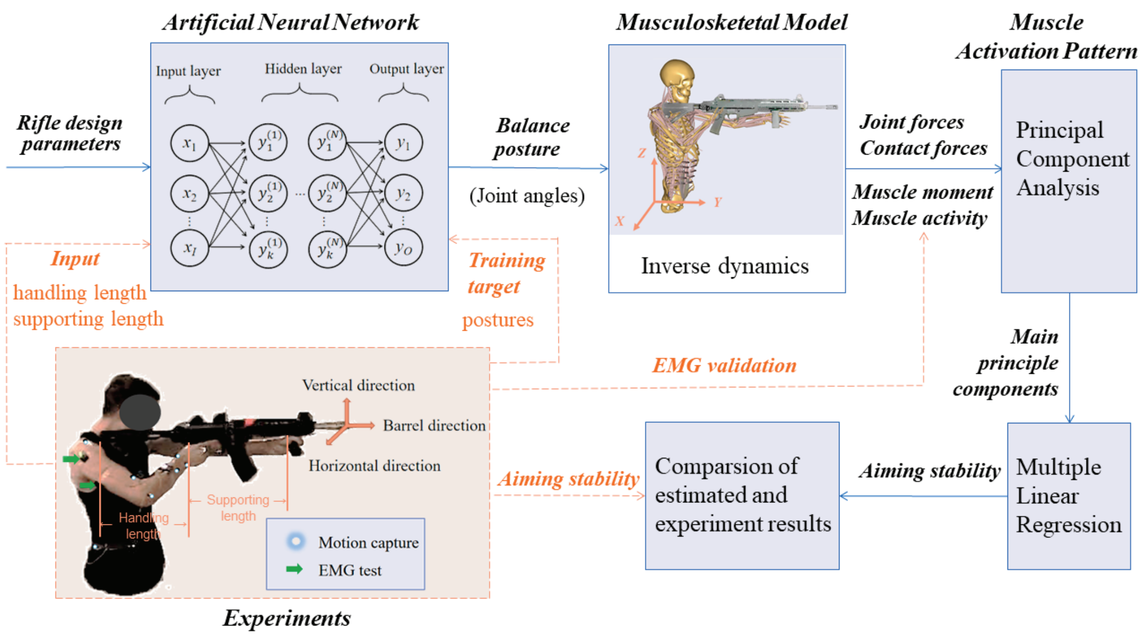

Fig. 1. Method for studying the performance and musculoskeletal biomechanics during aiming process under different human–gun parameters based on motion capture and musculoskeletal model

2.2. Experimental protocol

To investigate the effect of different handling length (i.e., the length from trigger to stock) and supporting length (i.e., the length from trigger to support position) on aiming stability, the experiment used a small caliber rifle with an adjustable buttstock and grip (Fig. 1). The handling length (HL) was adjusted from 31.5 to 39.5 cm, and the supporting length (SL) ranged from 25.5 to 34.5 cm. The tested supporting length was 25.5, 30.0, 33.0 (most shooters found the most comfortable length) and 34.5 cm, and the handling length was 31.5, 35.5, and 39.5 cm, and there were 12 experimental trails. After fully adapting to the rifle parameters, each subject randomly conducted 12 trails, aiming from a free-standing unsupported position at a target 100 m away. Each trail was repeated five times with sufficient rest after each test.

2.3. Motion capture and electromyography

The Codamotion Odin active optical 3D motion capture system obtained the trajectory of the upper body markers and the muzzle fluctuation under different handling length and supporting length, with a sampling frequency of 200 Hz. The marker motion was processed with a zero-phase second-order Butterworth filter with a cutoff frequency of 6 Hz, and the marker movement within one second before shooting was used to represent the aiming phase.

In order to capture the muzzle fluctuation, a marker point was positioned at the muzzle of the rifle, and the direction from the shooter's standing point to the aiming target was defined as the orientation of the barrel direction, as shown in Fig. 1. The aiming stability was characterized by the maximum magnitude of the muzzle fluctuation in the horizontal (perpendicular to the barrel), vertical (up and down), and barrel direction (Fig. 2). According to paper [30], the posture of lower body did not change during the aiming and shooting. As a result, 22 markers on the upper body for each subject were placed according to the guidelines for marker placements by Davis et al. [9]. The marker trajectories were exported in Coordinate 3D (.C3D) file format as the input of the "Inertial MoCap model" in AnyBody Managed Model Repository (AMMR v.2.1.1) to calculate the respective kinematic variables (i.e., joint angles).

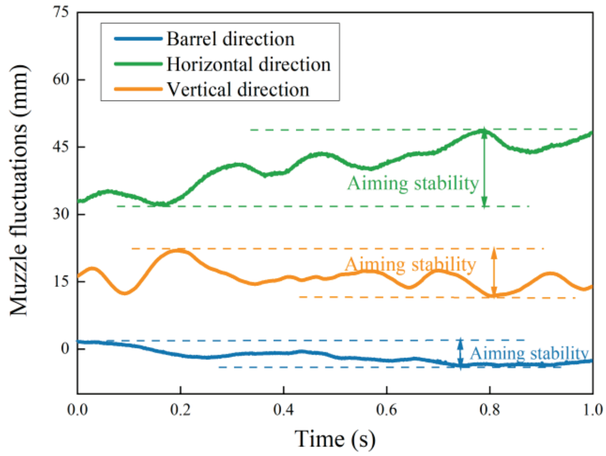

Fig. 2. The muzzle fluctuation of three directions

The sEMG of the biceps and triceps was acquired using the Delsys Trigno Wireless EMG System with a sampling frequency of 1000 Hz. The experimental procedure followed the directives of SENIAM [11] and used a band-pass filter between 10 and 400 Hz. Participants were required to undergo maximum voluntary contraction (MVC) tests based on Kendall's [5] manual muscle testing for normalization. The activation of the biceps and triceps was expressed as %MVC.

2.4. Artificial neural network

In order to maintain postural balance, the human posture changes with different handling length and supporting length. Since the human body is a complex nonlinear system, a back propagation (BP) neural network was established in order to map the human–gun parameters to the human balance posture.

The BP neural network consisted of the input layer, the hidden layer, and the output layer. The input layer contained five nodes for handling length, supporting length, and their quadratic term. The hidden layer consisted of 100 nodes. The output layer was the upper body posture, which included 25 joint angles such as

Table 1. Hyperparameters for the BP neural network

Weight initialization	Optimizer	Batch size	Epoch	Activation function	Learning rate	Loss function	Dropout probability
Random normal	Adam	10	2000	ReLU	0.02	MSEloss	0

pelvic rotation, elbow flexion, and shoulder abduction.

The hyperparameters for the BP neural network are listed in Table 1. One experimental test from each trail was randomly selected as the test data, and the remaining tests were the training data. RMSE and R^2 were used as the model error metrics.

2.5. Musculoskeletal model

In order to obtain the joint reaction forces and muscle activation of different balance postures, a musculoskeletal model of the upper body holding the rifle was established based on the "Free Posture Model" (AMMR v. 2.1.1), and the pelvis was connected to the ground by the spherical joints (Fig. 1). The geometric and inertial parameters of the musculoskeletal model were scaled to the average height and weight of the subjects by applying a length-mass-fat scaling law [10], [24].

During aiming and shooting, there are four contact areas between the body and the rifle: right shoulder, right hand, left hand and right cheek. It was assumed that the change in rifle weight distribution caused by different handling length was not taken into consideration. The rigid body of the rifle was built using the mass, center of mass, and rotational inertia of the test rifle. Since the contact force between cheek and rifle was small [23], the musculoskeletal model excluded the contact between cheek and rifle. Both hands and the rifle model were connected by spherical joints. The right shoulder and the rifle model were attached by the revolute joint.

The inverse dynamics were solved by quadratic muscle recruitment. The quadratic muscle recruitment solves an optimization problem with an objective function G, which tries to minimize the normalized forces (1) while subjecting them to the dynamic equilibrium Eq. (2) and restricting the muscles to pull only [7].

$$\min G(f^{(M)}) = \sum_{i=1}^{n^{(M)}} \left(\frac{f_i^{(M)}}{N_i} \right)^2 , \tag{1}$$

$$Cf = d , \tag{2}$$

$$0 \le f_i^{(M)} \le N_i , \quad i \in \{1, ..., n^{(M)}\} , \tag{3}$$

where G is the second-order quadratic objective cost function. $f^{(M)}$ is the muscle forces, and $f = [f^{(M)T}\ f^{(R)T}]$, $f^{(M)}$ is the muscle forces, $f^{(R)}$ is the joint reactions. $f_i^{(M)}$ is the i-th muscle force, N_i is the strength of the muscle and $n(M)$ is the number of muscles. Equation (2) is the dynamic equilibrium equations, which enter as constraints into the optimization. C is the coefficient-matrix for the unknown forces, and d contains all known applied loads and inertia forces. The non-negativity constraints on the muscle forces, Eq. (3), state that muscles can only pull, not push, and the upper bounds limit their capability. The core principles of the inverse dynamics approach used in this study are illustrated in Eqs. (1)–(3). These equations focus on the muscle recruitment strategy, and the detailed description of the computational process is provided in work [7].

The joint reaction forces, contact forces, muscle moment and muscle activation were calculated by the musculoskeletal model with different balance postures affected by the human–gun parameters. The muscle activation pattern solved by inverse dynamics makes the specific movement [15], and the muscle activation pattern can be reconstructed using a weighted linear combination of a small number of muscle synergies [8]. As a result, the principal component analysis was used to identify the muscle activation pattern of 44 upper body muscles with various balance postures.

2.6. Statistical analysis

The mean and standard deviation values of aiming stability, balance posture (i.e., joint angles) and muscle %MVC were calculated for each experimental trail. RMSE (root-mean-square error) and R^2 (coefficient of determination) were used to evaluate the neural network model and linear regression. Pearson correlation coefficients were computed to examine the relationship between calculated muscle activation and test %MVC, balance posture and joint reaction forces. Two-way, repeated measures analysis of variance (ANOVA) was used to study the effects of handling length and supporting length on aiming stability, balance posture, and biomechanics. Principal component analysis (PCA) was used to identify the components of muscle activation with different balance postures. The number of components was determined by a minimum eigenvalue of 1.0 and a minimum of 5% variance accounted for by each component. Finally, multiple regression analysis was used to describe the aiming stability in three directions by the components of PCA. The level of statistical significance was set at 0.05.

3. Results

3.1. Aiming stability

The muzzle fluctuation was obtained using the motion capture system. In Figure 2, a typical example

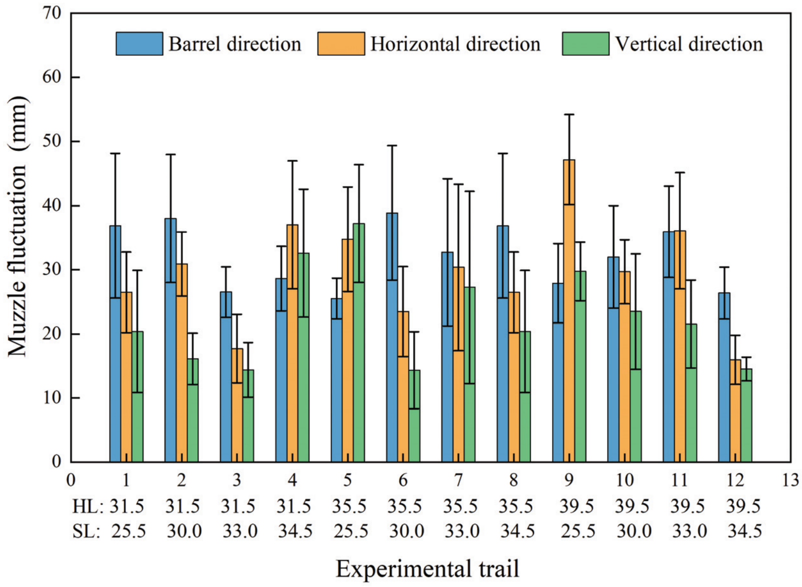

Fig. 3. The measurements of aiming stability with 12 experiment trails

of the time variation of muzzle fluctuation in one second before trigger pull is illustrated. The measurements of aiming stability from the experiments are displayed in Fig. 3. It shows that the muzzle fluctuation in horizontal and vertical directions was reduced when the shooters were in their most comfortable position (trail 3: 31.5 HL, 33.0 SL) and when the handling length and supporting length were the longest (trail 12: 39.5 HL, 34.5 SL). The ANOVA of aiming stability found that the interaction of handling length and supporting length had a significant effect on the aiming stability of horizontal direction ($F = 5.884$, $p = 0.001$) and barrel direction ($F = 2.859$, $p = 0.037$), but had no evident impact on the aiming stability of vertical direction.

3.2. Balance posture

The joint angles were calculated from the marker placed on the shooter's body. To examine the influence of human–gun parameters on balance posture, the ANOVA found that the significant effects of handling length on balance posture in descending order were right glenohumeral external rotation ($F = 35.305$, $p = 0$), right elbow flexion ($F = 7.101$, $p = 0.026$), and pelvis rotX ($F = 5.193$, $p = 0.049$). In Table 2, the body posture affected by the supporting length is illustrated. The pelvic posture and right glenohumeral flexion were not influenced by the supporting length.

The balance posture was affected by the human–gun parameters. The BP neural network was established to map the handling length and supporting length to the body balance posture. In Figure 4, the correspondence between the BP neural network's predicted outputs and the actual experimental results of the pelvic posture is presented. The R^2 value for the BP neural network predictions and experimental results of balance posture was greater than 0.95, which indicated that the BP neural network can simulate balance posture with different handling length and supporting length.

Table 2. The *F* value of ANOVA of supporting length on balance posture

Balance posture	Right side	Left side
Sterno Clavicular Protraction	20.752***	31.743***
Sterno Clavicular Elevation	9.662**	18.192**
Sterno Clavicular Axial Rotation	8.850*	17.857**
Glenohumeral Flexion		20.213**
Glenohumeral Abduction	19.325**	34.240***
Glenohumeral External Rotation	25.783***	12.517**
Elbow Flexion	5.203*	8.377*
Elbow Pronation	18.083**	48.055***

Significant correlation * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

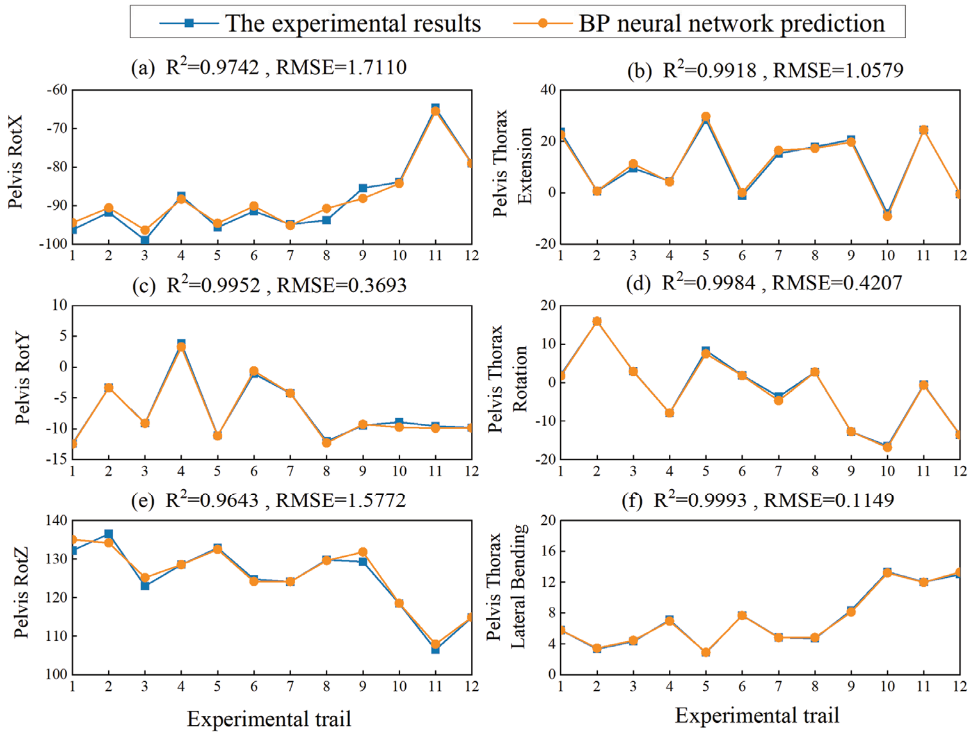

Fig. 4. Comparing BP neural network predictions for pelvis posture angles (in degrees) with the experimental results on 12 trials

3.3. Human–gun musculoskeletal biomechanics

The joint reaction forces, muscle moment, muscle activation, and contact forces between body and rifle with different balance postures were calculated by the human–gun musculoskeletal model. In Figure 5, the muscle activation of both arm triceps was correlated with the experimental %MVC of triceps muscles (left: $r = 0.719$, $p = 0.029 < 0.05$; right: $r = 0.823$, $p = 0.017 < 0.05$) is shown, indicating that the established musculoskeletal model was valid.

As demonstrated in Fig. 6 from the ANOVA study, the handling length and supporting length significantly affected the human–gun musculoskeletal biomechanics.

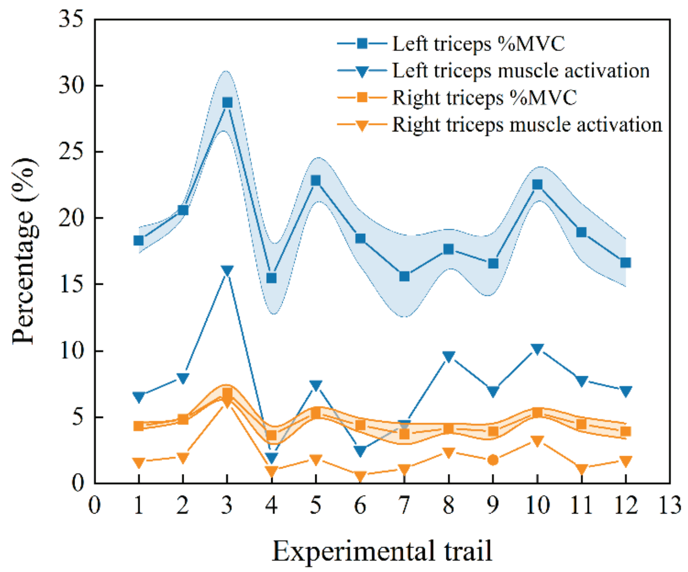

Fig. 5. The comparison of the experimental %MVC (with error bars) and calculated results of triceps muscles. There was a correlation between the two trends

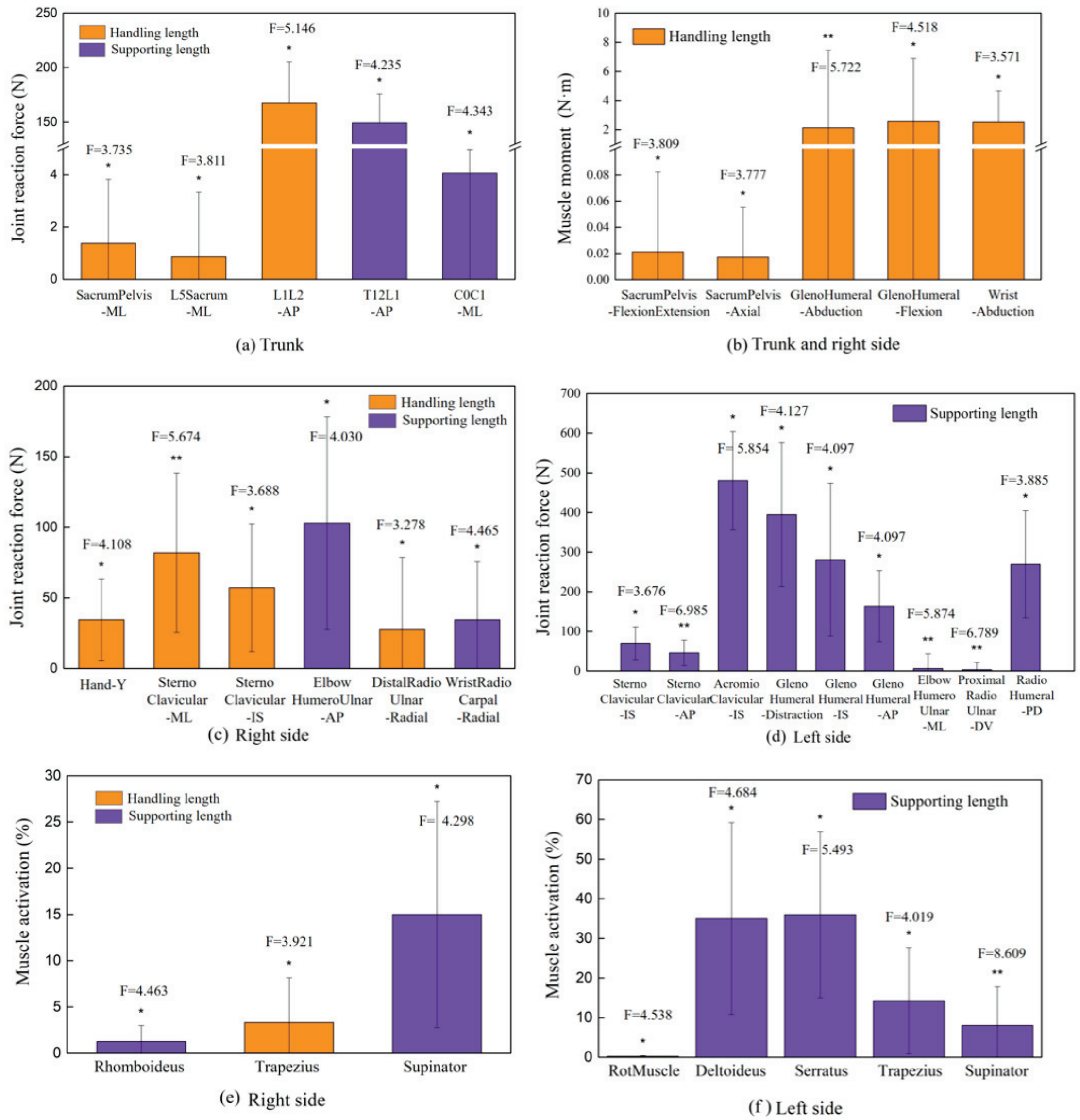

Fig. 6. The effect of handling length and supporting length on joint reaction forces, contact force, muscle moment (joint moment only by muscles), and muscle activation. The joint reaction forces, contact force, muscle moment, and muscle activation are the average of 12 trails. Orange color is influenced by handling length, purple color is affected by supporting length, and the F value of ANOVA is shown in the figure. The contact force directions are displayed in Fig. 1. Y direction is the direction from the shooter's position to the shooting target. Abbreviations for the joint reaction force direction: AnteroPosterior (AP); MedioLateral (ML); InferoSuperior (IS); ProximoDistal (PD); DorsoVolar (DV)

The sternoclavicular, glenohumeral, and elbow of both arms as well as the right hand reaction forces were greatly influenced by the human-gun parameters. The trapezius and supinator muscles of both arms were significantly affected, and supporting length had more impacts on the joints and muscles. The right arm's glenohumeral abduction muscle moments were most influenced by the handling length ($F = 5.722$, $p = 0.008$), and the left arm's supinator muscle activation was most impacted by the supporting length ($F = 8.609$, $p = 0.003$).

3.4. Muscle activation pattern

The muscle activation pattern of holding rifle during the aiming process was described by the principal component analysis. It revealed six principal components (PCs) in muscle activation for different handling length and supporting length, which explained 97.571% of the total variance (Fig. 7). PC 1, the muscles of left side, contained the shoulder, elbow and back muscles. PC 2, the muscles of right side, included the shoulder

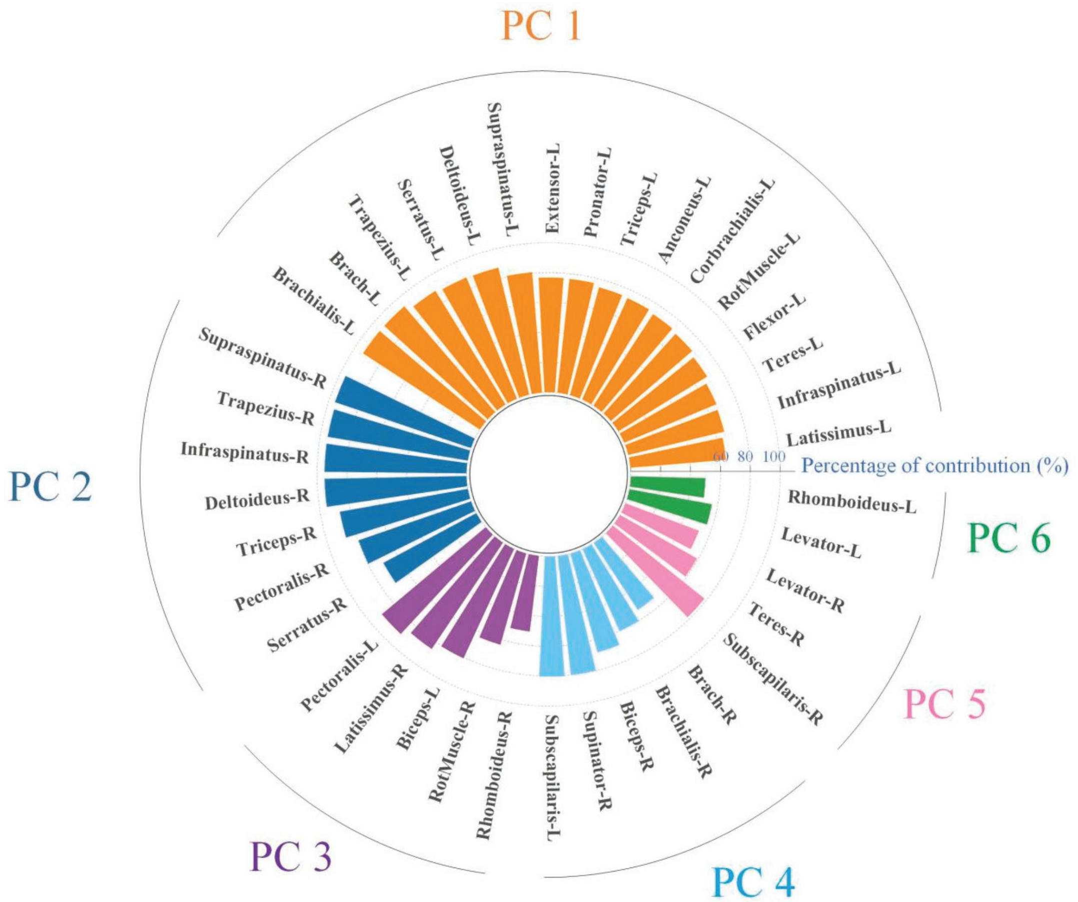

Fig. 7. Principal component analysis (varimax rotation) rotated solution of the calculated muscle activation from various handling length and supporting length. Six principal components and its factor loadings of absolute value greater than 0.5 are shown. *R* represents the right side, *L* is the left side

muscles, triceps and pectoralis. PC 3 described the muscles of the left biceps and pectoralis, and back muscles of right side. PC 4 presented the right elbow muscles and left subscapilaris. PC 5 was the muscles at the right scapula, and PC 6 was the back muscles on left side.

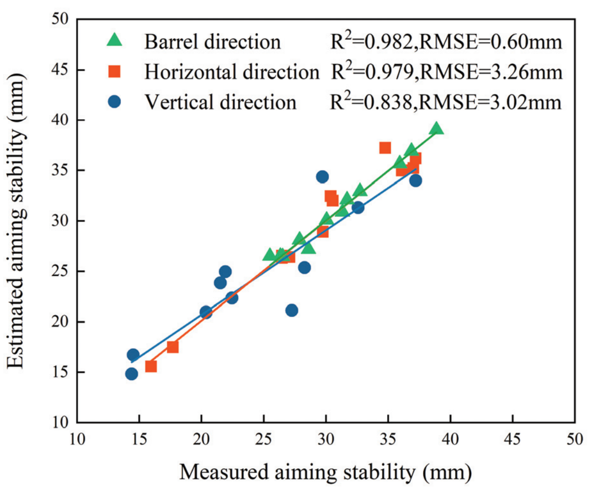

Fig. 8. Comparison of measured and estimated aiming stability in three directions

The identified muscle activation pattern was used to describe the aiming stability by the multiple regression analysis, and it showed that the six PCs of muscles explained 83.8–98.2% of the variance in aiming stability (Fig. 8). It suggested that it is possible to get a reasonable estimation of aiming stability from the human–gun parameters using the artificial neural network and musculoskeletal model.

3.5. Aiming performance

Based on the above method, with the handling length in the range of 31.5–39.5 cm and supporting length in the range of 25.5–34.5 cm, the balance posture was obtained by the neural network, and the muscle activation was solved by the musculoskeletal model. The aiming stability was described by the muscle activation pattern, as shown in Fig. 9.

Consistent with the experimental results, the muzzle fluctuation in horizontal direction was minimized when the shooters were in their most comfortable position

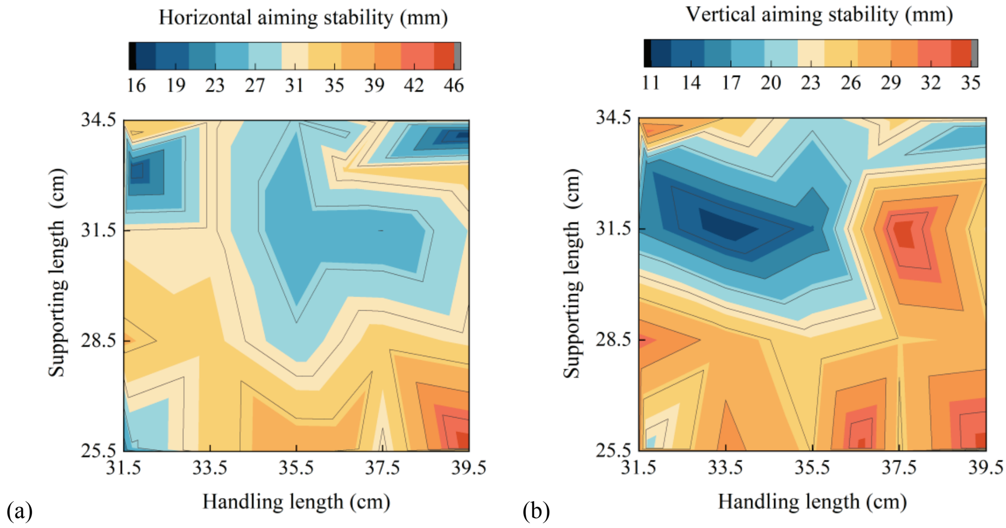

Fig. 9. (a) The aiming stability in horizontal direction and (b) the aiming stability in vertical direction

(31.5 HL, 33.0 SL) and when the handling length and supporting length were the longest. No other human–gun parameters that might have improved aiming stability were discovered. The vertical aiming stability was consistent with the experimental results, and when the handling length and supporting length were approximately 33.5 and 31.5 cm, respectively, there was better aiming stability in the vertical direction.

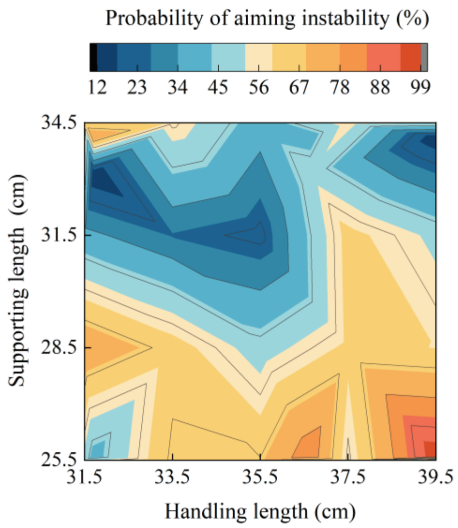

Fig. 10. The probability of aiming instability was calculated by normalizing and coupling the horizontal and vertical aiming stability to represent the aiming performance. The higher the aiming instability probability, the larger the amplitude of the muzzle fluctuation, and the more unstable the rifle is held

In order to optimize the aiming performance of shooters and improve the training efficiency, the horizontal and vertical aiming stability, which had an impact on shooting performance, were normalized and coupled to obtain the combined aiming performance. As shown in Fig. 10, the following human–gun parameters are more suitable for improving the aiming performance of shooters (1.75 m, 70 kg): a) the most comfortable position: handling length of 31.5 cm and supporting length of 33 cm; b) the maximum length for both handling and supporting length; and c) the handling length is 35.5 cm and the supporting length is 31.5 cm. The situation where the handling length is the maximum and the supporting length is the minimum should be avoided.

4. Discussion

In this study, we analyzed the effect of handling length and supporting length on aiming stability and musculoskeletal biomechanics, and estimated the aiming stability by the muscle activation pattern. The artificial neural network simulated the balance posture by handling length and supporting length. The human–gun musculoskeletal model obtained joint reaction forces and muscle activation with different balance postures. The six components of muscle activation explained 83.8–98.2% of the variance in aiming stability.

The ANOVA revealed that the interaction effect of handling length and supporting length had a significant impact on aiming stability, but the handling length and supporting length of each alone did not make an evident difference to aiming stability. In contrast to the conclusion that "handling length has a significant effect on aiming stability", Yuan and Lee's study [32] did not take the supporting length into consideration. As shown in Table 2, a series of changes in balance posture occur for the varied supporting length in order to maintain postural balance, while the posture changes are also affected by the handling length. The handling length and supporting length alter the balance posture simultaneously. Therefore, the two human–gun parameters are interacted and cannot be separated.

After fully adapting to the rifle, elite shooters' neural and muscle memory keeps the balance posture almost fixed. It has been seen that the proposed artificial neural network which simulates neural and muscle memory showed high accuracy in estimating the balance posture from the two human–gun parameters (Fig. 4). For some human movements where neural and muscle memory keep the movement patterns stabilized after training, an artificial neural network can attempt to establish the mapping relationship between human–machine design parameters and human movement patterns.

The inverse dynamics solution of the human–gun musculoskeletal model developed for various balance postures with different handling length and supporting length was tested (Fig. 5). The contact forces between human and rifle were consistent with the study [23], [27], with the largest force at the shoulder, followed by the right hand, and the smallest force at the left hand. The handling length had a significant impact on the contact force at the right hand in the *Y* direction ($F = 4.108$, $p = 0.025$), showing that the contact force of right hand is greatly affected by the handling length.

The correlation analysis between posture and calculated forces found that the contact forces at the shoulder in *X* and *Z* directions were strongly correlated with the pelvis rot*Y* and pelvis thorax extension, while the contact force at the shoulder in *Y* direction was not related to the body posture (Table 3). The contact force at right hand in *Y* direction was also strongly

Table 3. Pearson correlation coefficient *R* values between posture and calculated forces

Calculated forces	Pelvis rot*Y*	Pelvis thorax extension	Right Sterno Clavicular elevation	Right Sterno Clavicular axial rotation
The contact force at the shoulder in *X* direction	0.922***	–0.959***	0.915***	0.923***
The contact force at the shoulder in *Z* direction	–0.928***	0.945***		
The contact force at right hand in *Y* direction	0.902***	–0.905***		
GlenoHumeral flexion muscle moment of right side	–0.971***	0.959***	–0.830**	–0.851**
GlenoHumeral external rotation muscle moment of right side		–0.883**		
GlenoHumeral external rotation muscle moment of left side		–0.805*		
Joint reaction force of GlenoHumeral in Distraction	0.815*	–0.855**		

Significant correlation * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

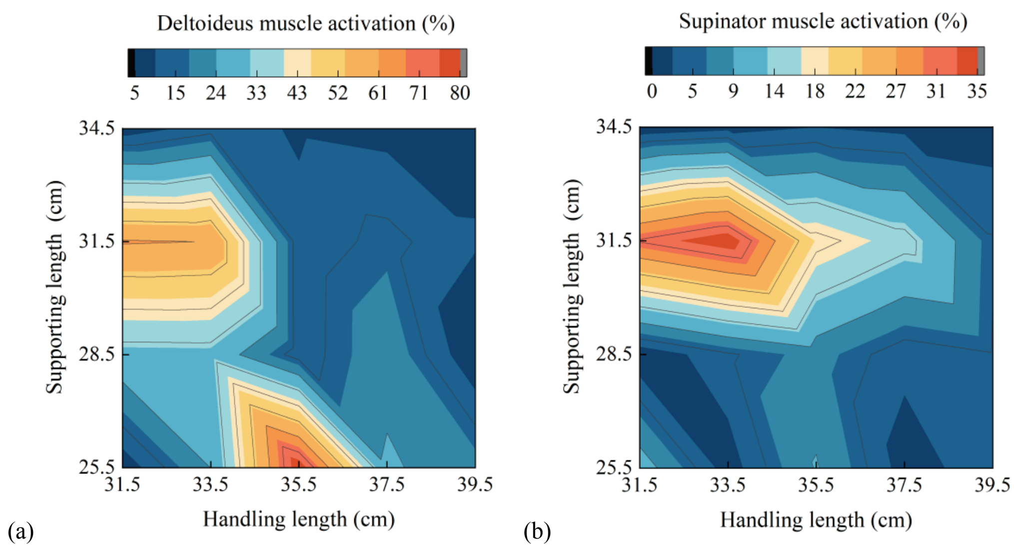

Fig. 11. (a) The deltoideus muscle activation of right arm and (b) the supinator muscle activation of left arm

correlated with the pelvis rot*Y* and pelvis thorax extension. However, the contact force of left hand was completely irrelevant to the posture, because the left arm mainly bears the weight of the rifle [25]. The glenohumeral muscle moment and joint reaction forces of both sides were correlated with the pelvis rot*Y* and pelvis thorax extension, while the remaining joint reaction forces, muscle moment, and muscle activation did not show any correlation with posture and may be influenced by other factors such as the weight and weight distribution of rifle.

The muscles that were most active during the aiming phase were the extensor (36.94%), deltoideus (23.91%), and serratus (20.48%) in the right arm, and the serratus (35.98%), deltoideus (35.00%), and flexor (20.24%) in the left arm. Right arm deltoideus muscle MVC was evaluated in relation to handling length [32], and we solved the deltoideus muscle activation of right arm within the range of the human–gun musculoskeletal model (Fig. 11a). Deltoideus muscle activation rose as handling length increased to 34 cm when the supporting length was less than 28.5 cm, which was consistent with the finding that the right deltoideus's MVC increased as handling length went from 28 to 33 cm [32]. However, when the handling length and supporting length were varied over a wider range, the human–gun parameters did not significantly affect muscle activation of the right deltoideus.

Figure 6 illustrates how the handling length and supporting length affect joint reaction forces, contact forces, joint moments, and muscle activation. In addition to the important joints which were SternoClavicular, GlenoHumeral, and elbow of both arms as well as right hand, the trapezius and supinator muscles of both arms that the experimental research have not been studied were significantly affected. The left arm's supinator muscle activation was most significantly impacted by supporting length. As shown in Fig. 11b, the supinator muscle activation was greatest at the supporting length of 31.5 cm, and the muscle activation decreased as the supporting length changed.

As shown in Fig. 8, multiple regression analysis revealed that the six principal components of muscle activation were able to describe aiming stability. PC 6 (back muscles of left side, $p = 0.028$), PC 1 (shoulder, elbow and back muscles of left side, $p = 0.033$), and PC 2 (shoulder, triceps and pectoralis muscles of right side, $p = 0.044$) all had a significant impact on the aiming stability in barrel direction. It indicated that the aiming stability in barrel direction was mainly affected by the shoulder and elbow muscles of both sides and the back muscles of left side of the body. The muscles that strongly influenced aiming stability in horizontal direction were PC 2 (shoulder, triceps and pectoralis muscles of right side, $p = 0.025$), and PC 4 (right elbow muscles and left subscapilaris, $p = 0.035$), suggesting that aiming stability in horizontal direction was greatly influenced by the shoulder, elbow and pectoralis muscles of the right arm. The PC 4 (right elbow muscles and left subscapilaris) and PC 2 (shoulder, triceps and pectoralis muscles of the right side) made the largest contribution to aiming stability in vertical direction, but the principal components did not significantly affect the aiming stability in vertical direction, which is consistent with the experimental analysis that the aiming stability in vertical direction was unaffected by the handling length and supporting length. The aiming stability in vertical direction might be related to the body sway [12] and heart rate [17].

The proposed model can be used to study the effects of handling length and supporting length on balance posture, joint forces, muscle moment, muscle activation, and aiming stability. The shooters could find more suitable human–gun parameters and enhance their performance by using this approach. Future studies will involve a larger sample size that makes more accurate predictions and establish a more general model that considers different human parameters and more human–gun parameters (such as the weight and weight distribution of rifles) to predict aiming stability and shooting performance. Moreover, this method could be exploited in situations where the human movement pattern is stabilized. An artificial neural network could obtain the movement pattern by simulating the function of neural and muscle memory. An inverse model of musculoskeletal dynamics can be used to study the biomechanics of this movement. The muscle activation pattern could be generated to find out how the central neural system can select appropriate groups of muscles to make the human movement.

The main limitation of this study is that the model developed is based on the human physiological parameters of 1.75 m and 70 kg, with the assumption of right-handed. The height and weight of these elite shooters are strictly controlled at around 1.75 m and 70 kg since shooters with a wide range in height and weight have markedly different balance postures for the same human–gun parameters. Therefore, the artificial neural network and the musculoskeletal model established in this paper are restricted to the aforementioned human parameters. The maximum handling length of 39.5 cm and the maximum supporting length of 34.5 cm are the boundary conditions of the model to hold the rifle steadily. The methodological framework introduced in this study demonstrates that it is possible to evaluate the effect of human–gun parameters on biomechanics and obtain a reasonable estimation of aiming stability, even though a constrained model boundary was used. This framework is applicable to both right-handed and left-handed weapon handling. We speculate that the main differences may lie in the balance postures, muzzle fluctuation, and the significance of biomechanical responses to changes in rifle parameters when comparing left-handed to right-handed shooters. This study paves the way for more elaborate studies going forward.

5. Conclusions

The performance and musculoskeletal biomechanics of the aiming process under different handling length and supporting length was evaluated based on motion capture and musculoskeletal model. Different handling length and supporting length led to the change in balance posture. The balance posture affected the joint reaction forces and muscle activation. The muscle activation pattern could describe the aiming stability (83.8–98.2%), and thus the handling length and supporting length influenced the aiming stability. It was also found that the trapezius and supinator muscles were greatly affected by the handling length and supporting length. The shoulder, elbow and pectoralis muscles of the right arm could influence the aiming stability. The findings might provide insight into the effect of human–gun parameters on aiming stability and optimize human–gun parameters to reduce muscle fatigue, prevent musculoskeletal injuries, and improve shooting performance.

Conflicts of interest

The authors declare no conflicts of interest.

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References

[1] BALL K.A., BEST R.J., WRIGLEY T.V., *Body sway, aim point fluctuation and performance in rifle shooters: inter and intra-individual analysis*, J. Sports Sci., 2003, 21 (7), 559–566.

[2] BROWN S.A.T., MITCHELL K.B., *Shooting stability: A critical component of marksmanship performance as measured through aim path and trigger control*, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2017, 61 (1), 1476–1480.

[3] CHOI Y.J., LEE Y.S., LEE S.H., CHAE J.W., CHOI E.J., HONG S.K., *Impact path analysis of human body with three typical shooting postures*, Key Engineering Materials, 2006, 326–328, 899–902.

[4] COLEMAN J.L., DAVEY P., MCCLELLAND J.A., MIDDLETON K.J., *The use of small-arms stability measures in combat shooting assessments*, Appl. Ergon., 2025, 122, 104385.

[5] CONROY V.M., MURRAY JR. B.N., ALEXOPULOS Q.T., MCCREARY J., *Kendall's muscles: testing and function with posture and pain*, 6th ed., Lippincott Williams & Wilkins, 2022, 271–297.

[6] CORRIVEAU D., RABBATH C.A., GOUDREAU A., *Effect of the firing position on aiming error and probability of hit*, Defence Technology, 2019, 15 (5), 713–720.

[7] DAMSGAARD M., RASMUSSEN J., CHRISTENSEN S.T., SURMA E., DE ZEE M., *Analysis of musculoskeletal systems in the Any Body Modeling System*, Simulation Modelling Practice and Theory, 2006, 14 (8), 1100–1111.

[8] D'AVELLA A., PORTONE A., LACQUANITI F., *Superposition and modulation of muscle synergies for reaching in response to a change in target location*, Journal of Neurophysiology, 2011, 106 (6), 2796–2812.

[9] DAVIS R.B., ÕUNPUU S., TYBURSKI D., GAGE J.R., *A Gait Analysis Data Collection and Reduction Technique*, Human Movement Sci., 1991, 10 (5), 575–587.

[10] FRANKENFIELD D.C., ROWE W.A., COONEY R.N., SMITH J.S., BECKER D., *Limits of body mass index to detect obesity and predict body composition*, Nutrition, 2001, 17 (1), 26–30.

[11] HERMENS H.J., FRERIKS B., DISSELHORST-KLUG C., RAU G., *Development of recommendations for SEMG sensors and sensor placement procedures*, Journal of Electromyography and Kinesiology, 2000, 10 (5), 361–374.

[12] IHALAINEN S., KUITUNEN S., MONONEN K., LINNAMO V., *Determinants of elite□level air rifle shooting performance*, Scandinavian Journal of Medicine & Science in Sports, 2016, 26 (3), 266–274.

[13] IHALAINEN S., LINNAMO V., MONONEN K., KUITUNEN S., *Elite rifle shooters'technique test measures are related to competition performances*, Int. J. Sports Physiol. Perform., 2015, 29 (1), 182–184.

[14] JIN X., ZHOU K.D., LEI H.E., HUANG X.Y., ZHANG J.B., *Dynamic simulation for a human gun system model with successive shootings based on life mod*, Journal of Vibration and Shock, 2015, 34 (23), 68–71.

[15] KAWATO M., *Internal models for motor control and trajectory planning*, Current Opinion in Neurobiology, 1999, 9 (6), 718–727.

[16] KEMNITZ C.P., JOHNSON R.F., MERULLO D.J., RICE V.J., *Relation of rifle stock length and weight to military rifle marksmanship performance by men and women*, Perceptual and Motor Skills, 2001, 93 (2), 479–485.

[17] KONTTINEN N., LYYTINEN H., VIITASALO J., *Rifle-balancing in precision shooting: behavioral aspects and psychophysiological implication*, Scandinavian Journal of Medicine and Science in Sports, 1998, 8 (2), 78–83.

[18] KUO C.L., YUAN C.K., LIU B.S., *Using human-centered design to improve the assault rifle*, Appl. Ergon., 2012, 43 (6), 1002–1007.

[19] LANG D., ZHOU A., *Relationships between postural balance, aiming technique and performance in elite rifle shooters*, European Journal of Sport Science, 2022, 22 (10), 1493–1498.

[20] LEE Y.S., CHOI Y.J., HAN K.H., CHAE J.W., CHOI E.J., KIM I.W., *A study on the human impulse characteristics with standing*

shooting posture, Key Engineering Materials, 2005, 297–330, 2314–2319.

[21] MASON B.R., COWAN L.F., BOND J., *Biomechanical factors affecting accuracy in pistol shooting*, J. Biomech., 1989, 22 (10), 1052.

[22] MONONEN K., KONTTINEN N., VIITASALO J., ERA P., *Relationships between postural balance, rifle stability and shooting accuracy among novice rifle shooters*, Scand. J. Med. Sci. Sports, 2007, 17 (2), 180–185.

[23] MORELLI F., NEUGEBAURE J.M., HAYNES C.A., FRY T.C., ORTEGA S.V., STRUVE D.J., LAFIANDRA M.E., LARKIN G.B., *Shooter-System Performance Variability as a Function of Recoil Dynamic*, Human Factors, 2017, 59 (6), 973–985.

[24] RASMUSSEN J., DE ZEE M., DAMSGAARD M., CHRISTENSEN S.T., CLEMENS M., SIEBERTZ K., *A general method for scaling musculo-skeletal models*, Proceedings of the 10th International Symposium on Computer Simulation in Biomechanics, 2005.

[25] SELINGER J.C., *The effect of weight and weight distribution on upper extremity muscular fatigue during static rifle aiming*, Master's dissertation, Queen's University, Canada, 2009.

[26] STONE R.T., MOELLER B.F., MAYER R.R., ROSENQUIST B., RYSWYK D.V., EICHORN D., *Initial Biomechanical and Performance Implications of Weapon Design: Comparison of Bullpup and Conventional Configurations*, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2014.

[27] TARASZEWSKI M., EWERTOWSKI J., *Complex experimental analysis of rifle-shooter interaction*, Defence Technology, 2017, 13 (5), 346–352.

[28] VIBOCH T., STURDY J., WOLF A., HALUCH K., SESSOMS P., *Effect of rifle firing position on upper body muscle activity in US Marines during simulated 100-yard marksmanship tasks*, Journal of Science and Medicine in Sport, 2017, 20, S175.

[29] VIITASALO J.T., ERA P., KONTTINEN N., MONONEN H., MONONEN K., NORVAPALO K., RINTAKOSKI E., *The posture steadiness of running target shooters of different skill levels*, Kinesiology, 1999, 31, 18–28.

[30] WANG Y., WANG Y.P., WANG X.R., XU C., *Human-rifle Dynamic Response Analysis Using Inverse Dynamics in Shooting Process*, Journal of Vibration and Shock, 2020, 40 (10), 288–295.

[31] YANG Y., WANG Y.P., XU C., *Human-rifle musculoskeletal model and its inverse dynamic simulation*, Journal of Vibration and Shock, 2018, 37 (9),100–105.

[32] YUAN C.K., LEE Y.H., *Effects of rifle weight and handling length on shooting performance*, Appl. Ergon., 1997, 28 (2), 121–127.