

Changes in squat strength and kendo men-strike biomechanics after velocity-based and percentage-based resistance training: an exploratory comparison

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ABSTRACT

Purpose. This exploratory study compared changes in squat strength and kendo men-strike biomechanics between velocity-based training (VBT) and percentage-based training (PBT) conditions.

Methods. Twelve university kendo athletes completed a 7-week back-squat intervention under VBT ($n = 7$) or PBT ($n = 5$). Allocation was based on academic year rather than randomisation. Before and after training, squat one-repetition maximum (1RM), men-strike motion time, push-off-phase rate of force development over 0–100 ms (RFD0–100 ms), and the temporal overlap of high-extension-torque phases among the hip, knee, and ankle joints were assessed.

Results. Absolute and relative squat 1RM increased in both conditions. Between-condition differences in change were 14.1 kg for absolute 1RM (95% CI [4.5, 23.8]) and 0.309 kg · kg⁻¹ for relative 1RM (95% CI [0.136, 0.482]), favouring VBT. The between-condition difference for RFD0–100 ms also favoured VBT (27.62 N · kg⁻¹ · s⁻¹; 95% CI [-11.75, 66.98]), but the CI included zero. Differences were small and uncertain for men-strike motion time (-0.025 s; 95% CI [-0.142, 0.092]) and the overlap index (1.6 percentage points; 95% CI [-4.8, 8.1]).

Conclusions. Between-condition differences were clearest for squat strength, whereas evidence for kendo-specific biomechanical changes was limited. Because academic year was confounded with intervention condition, and the interventions differed in load progression and autoregulation, the findings cannot be attributed to velocity feedback alone. Evidence for transfer to faster men-strike performance remains inconclusive.

Key words: muscle strength, athletic performance, biomechanical phenomena, kinetics, weight lifting

Introduction

Kendo men-strike motion is an explosive movement in which a player rapidly propels the body over a relatively short distance and delivers a valid strike immediately after deciding to attack during an offensive-defensive interaction with an opponent. Among the various striking techniques used in kendo, the men-strike, in which the player jumps forward while striking the opponent's head target, is one of the most frequently performed fundamental techniques in competition. The rapid execution of this movement is considered an important factor that may influence match outcomes. Therefore, understanding the force-production characteristics underlying kendo striking motion from a biomechanical perspective is of considerable importance.

Previous biomechanical studies have described lower-limb joint-torque and ground-reaction-force characteristics during the kendo men-strike motion, including temporal features of push-off mechanics [1, 2]. These findings suggest that the rapidity of striking motion may depend not only on the maximal muscle strength itself but also on temporal force-production characteristics and the organisation of lower-limb joint torques.

Rate of force development (RFD) is widely used as an indicator of explosive force-producing capability. It reflects the ability to generate force rapidly within a short period of time and has been recognised as an important determinant of performance in explosive movement tasks, such as jumping and sprinting [3]. Furthermore, resistance training performed with an

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explosive intent to generate force has been shown to be effective for improving RFD [4]. However, to the best of our knowledge, no previous training-intervention study has examined changes in task-specific push-off-phase RFD or the temporal overlap of high-extension-torque phases during the kendo men-strike motion.

In recent years, velocity-based training (VBT) has gained increasing attention as an alternative method for prescribing resistance-training loads, in addition to the traditional percentage-based approach using a percentage of one-repetition maximum (%1RM). VBT uses movement velocity to monitor performance and guide load prescription. In the present study, participants in both conditions (VBT and PBT) were instructed to perform each concentric phase with maximal intended velocity. Previous studies have reported that VBT and velocity-feedback resistance training can influence explosive performance measures, such as sprinting and jumping [5, 6]. Furthermore, a systematic review has summarised the effects of VBT on one-repetition maximum strength, vertical jump performance, and sprint performance [7]. Nevertheless, little is known about whether VBT influences force-production characteristics and the temporal organisation of lower-limb joint torques during the kendo men-strike motion.

Therefore, the purpose of this exploratory study was to compare pre-to-post changes in biomechanical characteristics of the kendo men-strike motion between VBT and PBT conditions in university kendo athletes. Specifically, push-off-phase RFD, the temporal overlap of high-extension-torque phases among the three lower-limb joints, and men-strike motion time were analysed.

Material and methods

Participants

Fourteen university kendo athletes were initially recruited. Two participants did not complete the intervention because of absence, injury, or scheduling conflicts and were excluded from the analysis. The final analysis included 12 participants who completed all 14 scheduled training sessions and both pre- and post-intervention measurements. The VBT condition comprised seven participants (three men and four women), and the PBT condition comprised five participants (three men and two women).

Study design

This non-randomised comparative study examined pre-to-post changes following a 7-week back-squat intervention. Participants were allocated according to

academic year: first-year students to the VBT condition, and students in their second year or above to the PBT condition. Thus, academic year was completely confounded with intervention condition.

Before and after the intervention, participants completed squat one-repetition maximum (1RM) testing and the kendo men-strike protocol. The strike procedure, shinai-angle calculation, and event definitions were based on previous studies [1, 8].

Instrumentation

The men-strike motion was recorded using 12 high-speed cameras (Miquis, Qualisys AB, Gothenburg, Sweden) at 200 Hz and a force plate (9287C, Kistler Instrumente AG, Winterthur, Switzerland) at 1000 Hz. The camera system was calibrated according to the manufacturer's procedures. The mean of the camera-wise average residuals was 3.37 mm (range, 1.99–7.14 mm), and the standard deviation of the reconstructed wand length was 2.77 mm. The calibration was recorded as passed by the acquisition software. The cameras and force plate were synchronised using a common hardware trigger.

Three-dimensional whole-body kinematics were estimated at 200 Hz using Theia3D (Theia Markerless Inc., Kingston, ON, Canada). Pose-format C3D files were imported into Visual3D (C-Motion Inc., Germantown, MD, USA), where a biomechanical model was generated and the required joint-centre and segment-centre-of-mass data were exported.

One marker was attached to the shinai tip and two markers near the tsuba to calculate shinai angle and angular velocity.

Men-strike motion procedure

The experimental conditions for the men-strike motion were established based on previous studies [1, 8]. However, unlike previous studies using external stimuli such as LED signals, participants in the present study initiated the strike at a self-selected time and were instructed to perform the movement with maximal effort.

Participants assumed a *chudan-no-kamae* stance on the force plate and performed the trials without wearing protective armour, using light clothing that did not interfere with movement. The striking target was a practice dummy equipped with kendo armour. The distance to the target was set at 2.3 m from the toe of the rear foot (push-off leg).

Trials were repeated until three strikes considered successful by the participant were obtained. Adequate

rest intervals were provided between trials to minimise the effects of fatigue.

Selection of the analysis trial

For the primary analysis, the successful trial with the shortest men-strike motion time was selected *a priori* for each participant at each measurement time point.

Because men-strike motion time was treated as a performance outcome, the fastest successful trial was prespecified to represent each participant's best successful performance. The same trial was used for motion time, RFD, overlap index, and waveform analyses.

Sensitivity analyses used the mean of all valid trial-specific values. If fewer than three valid trials were available because of a technical error, the remaining trials were averaged for the sensitivity analysis, but the participant-by-time-point cell was excluded from reliability analyses requiring three trials.

Squat one-repetition maximum (1RM) testing

Squat one-repetition maximum (1RM) was assessed using a high-bar back squat under the supervision of experienced investigators. Squat depth was standardised to approximately 90° of knee flexion, as visually confirmed by the investigators. The load was progressively increased until 1RM was determined, with reference to the procedure described by Sunagawa and Furugen [9].

A minimum rest interval of 3 min was provided between attempts. For safety, a squat rack and safety bars were used, and spotters were positioned on both sides of the participant. Before testing, participants received technical instruction and an opportunity to confirm squat form.

Training intervention

Participants completed back-squat training twice weekly for 7 weeks, with at least 48 h rest between sessions and 90 s of rest between sets. The squat technique and depth were the same as those used during 1RM testing. Both conditions entailed 24 repetitions *per* session, and participants were instructed to perform each concentric phase with maximal intended velocity. Participants continued their regular kendo practice but were instructed not to undertake additional resistance training.

Velocity-Based Training (VBT)

In the VBT condition, mean concentric velocity was measured using a linear position transducer (Vitrue, Speed4Lifts S.L., Barcelona, Spain), with feedback provided after every repetition. The target mean concentric velocity was $0.60 \text{ m} \cdot \text{s}^{-1}$, with an acceptable range of $0.54\text{--}0.66 \text{ m} \cdot \text{s}^{-1}$. This target was selected on the basis of the established inverse relationship between squat load and movement velocity [10]. However, because the velocity associated with a given percentage of 1RM may vary according to squat depth, the velocity metric used, fatigue, and inter-individual differences, and because individual load-velocity profiles were not established, the target range was used as an operational criterion for velocity-guided load autoregulation rather than as an exact equivalent of 80%1RM for every participant.

The initial load was selected to produce a velocity within the target range, taking into account the load used in the preceding session. Each set ended after eight repetitions or after two repetitions fell outside the target range, regardless of whether they occurred consecutively. The load for the next set was increased when velocity exceeded $0.66 \text{ m} \cdot \text{s}^{-1}$ and decreased when it fell below $0.54 \text{ m} \cdot \text{s}^{-1}$. Load adjustments were made in increments of 2.5 or 5.0 kg. Additional sets were performed as necessary to complete 24 repetitions; consequently, the number of sets could vary.

Percentage-Based Training (PBT)

In the PBT condition, participants performed three sets of eight repetitions using a fixed load equal to 80% of the pre-intervention 1RM. The 1RM was not reassessed, and the load remained unchanged throughout the intervention. Thus, relative intensity may have decreased as strength increased.

Although both conditions entailed 24 repetitions *per* session, they differed in load prescription, progression, velocity feedback, and number of sets. The PBT condition was prescribed using a fixed percentage of the pre-intervention 1RM, whereas the VBT condition was prescribed using a predefined movement-velocity range and session-by-session load adjustment. The two conditions were therefore not designed to provide precisely matched relative intensities throughout the intervention.

Data processing and calculated variables

Coordinate system and synchronisation

The laboratory coordinate system was defined as a right-handed coordinate system, with the X-axis rep-

representing the mediolateral direction, the *Y*-axis representing the anterior-posterior direction, and the *Z*-axis representing the vertical direction. Ground reaction force data and kinematic data were synchronised using a common hardware trigger signal, and all analyses were performed within the same laboratory coordinate system.

Smoothing and resampling procedures

A fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz was applied to the kinematic coordinates and ground reaction force data. The same cut-off was used for both data types to reduce inverse-dynamics artefacts caused by mismatched filtering [11]. Ground reaction force data were then resampled from 1000 to 200 Hz using linear interpolation. The filtered and resampled data were used to calculate joint torques and RFD.

Shinai marker coordinates were not filtered to preserve the abrupt change in angular velocity used to identify impact.

Calculation of centre of mass

Three-dimensional whole-body centre-of-mass (COM) coordinates were obtained from the biomechanical model generated in Visual3D using Theia3D output. The body segment inertial parameters used in Visual3D were based on the coefficients reported by Ae *et al.* [12].

The anterior-posterior and vertical COM velocity components were calculated by differentiating the corresponding COM coordinates. The resultant *YZ*-plane COM speed was used to identify movement onset.

Calculation of shinai angle and angular velocity

A vector extending from the midpoint of the two markers near the tsuba to the shinai tip marker was defined. Shinai angle was calculated as the angle between the projection of this vector onto the *YZ* plane and the negative *Y*-axis, based on Murase *et al.* [1]. Shinai angular velocity was obtained by differentiating the angle with respect to time.

Event definitions and men-strike motion time

Movement onset was defined as the first frame at which the resultant *YZ*-plane COM speed exceeded $0.15 \text{ m} \cdot \text{s}^{-1}$.

The impact instant was identified from shinai angular velocity. Specifically, the first frame at which shinai angular velocity became negative following the downswing was defined as the impact instant.

Men-strike motion time was defined as the duration from movement onset to the impact instant.

Ground reaction force

Ground reaction force was analysed using the anterior-posterior (*Y*-axis) and vertical (*Z*-axis) force components. The resultant *YZ*-plane ground reaction force was calculated from these two components and normalised to body mass ($\text{N} \cdot \text{kg}^{-1}$).

Rate of force development (RFD)

RFD was calculated from the non-time-normalised, filtered, and body-mass-normalised resultant ground reaction force data at 200 Hz. The reference point was defined as the minimum resultant force within 0.20 s after movement onset and was treated as the beginning of the subsequent force increase during push-off.

RFD0–50 ms and RFD0–100 ms were calculated as the change in force from the reference point to 50 and 100 ms, divided by 0.05 and 0.10 s, respectively. At 200 Hz, these periods corresponded to 10 and 20 sampling intervals. RFD0–100 ms was the primary outcome, whereas RFD0–50 ms was included in the supplementary reliability and sensitivity analyses. Both were expressed in $\text{N} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$.

Because RFD is sensitive to filtering and onset-identification procedures, the reference point was treated as an operational, task-specific definition rather than a conventional contraction onset [3, 13, 14].

Inverse dynamics and lower-limb joint torque

Hip, knee, and ankle net joint torques were not calculated using the built-in inverse dynamics function of Visual3D. Instead, two-dimensional inverse dynamics in the sagittal plane (*YZ* plane), based on the link-segment model described by Winter [15], was independently implemented using Excel VBA.

The inverse dynamics calculations used the ground reaction force components (F_y and F_z) acting on the push-off leg (left leg), lower-limb landmark coordinates exported from Visual3D (toe, fifth metatarsophalangeal joint, medial and lateral malleoli, medial and lateral femoral epicondyles, and hip joint centre coordinates in the *Y* and *Z* directions), and segment centre of mass coordinates (COM_LFT, COM_LSK, and COM_LTH *Y* and *Z* components).

The ankle joint centre and knee joint centre were defined as the midpoints between the corresponding medial and lateral landmarks.

The point of application of the ground reaction force was determined using the measured centre of pressure (COP) coordinates obtained from the force plate. The anterior-posterior (Y-axis) and vertical (Z-axis) COP coordinates were treated as the point of force application at each frame and incorporated into the inverse dynamics calculations.

Body segment inertial parameters, including segment mass ratios and moments of inertia, were determined based on Ae *et al.* [12] and scaled according to each participant's body mass and segment dimensions. The smoothed coordinate and ground reaction force data described above were used for analysis, and segment centre of mass acceleration and segment angular acceleration were calculated using numerical differentiation.

The calculated net joint torques were analysed as sagittal-plane flexion-extension torques, with extension torque defined as positive. To reduce the influence of body size differences, joint torques were normalised to body mass and expressed in $\text{N} \cdot \text{m} \cdot \text{kg}^{-1}$.

Time normalisation

Ground reaction force and joint-torque waveforms were time-normalised from movement onset (0%) to impact (100%) and resampled to 101 points. Primary waveform analyses used the fastest successful trial selected for each participant, and condition mean waveforms were calculated from these representative trials. Sensitivity analyses based on the mean of all valid trials were limited to the scalar RFD and overlap-index outcomes.

Temporal overlap index of high-torque phases

Based on previous kendo studies describing the temporal organisation of lower-limb joint torques during push-off [1, 2], an overlap index was calculated as an exploratory descriptor of the simultaneous high-extension-torque phases of the hip, knee, and ankle joints.

The analysis was restricted to 0–95% of normalised motion time (96 points). The final 5% was excluded because the push-off foot left the force plate, changing the support condition and potentially producing unstable force and joint-torque values. Within the 0–95% interval, time points at or above 50% of each joint's peak extension torque were identified. The overlap index was the percentage of the 96 points at which all three joints simultaneously met this criterion.

The 50% threshold was used for the primary analysis as a pragmatic half-maximum criterion. Sensitivity

analyses used thresholds of 40% and 60% while retaining the same interval and denominator. Sensitivity to trial selection was also examined using the mean of the trial-specific overlap-index values from all valid trials.

The overlap index was treated as a measure of high-torque temporal overlap rather than a comprehensive measure of inter-joint coordination.

Statistical analysis

Data are presented as mean $\pm$ standard deviation. Primary analyses used the fastest successful men-strike trial selected for each participant at each measurement time point.

Baseline differences and between-condition differences in pre-to-post change scores were quantified using Hedges' *g*, calculated as VBT minus PBT. Ninety-five percent confidence intervals for Hedges' *g* were obtained by inversion of the non-central *t* distribution. Absolute effect-size magnitudes were interpreted as small (0.2), moderate (0.5), or large (≥ 0.8) [16].

Because allocation was non-random and baseline strength differed between conditions, exploratory baseline-adjusted analyses were performed for each outcome. Post-intervention values were modelled using intervention condition and the corresponding baseline value, with HC3 heteroskedasticity-robust standard errors. Adjusted condition means were estimated at the pooled mean baseline value. A condition-by-baseline interaction was examined to assess the homogeneity-of-regression-slopes assumption. These analyses were exploratory and could not remove confounding by academic year or other unmeasured cohort characteristics.

Sensitivity analyses used the mean of all valid trial-specific values for RFD and the overlap index. The overlap index was also recalculated using thresholds of 40%, 50%, and 60% of each joint-specific peak extension torque. Results were summarised using Hedges' *g* and 95% confidence intervals.

Trial-to-trial reliability was assessed using two-way mixed-effects consistency intraclass correlation coefficients for a single trial [*ICC*(3,1)] and the mean of three trials [*ICC*(3, *k*), *k* = 3]. Typical error, typical error relative to the mean, and the mean within-participant coefficient of variation were also calculated. Reliability analyses included only participant-by-time-point cells with three valid trials.

Where reported, statistical significance was set at $p < 0.05$. Given the small sample size, interpretation emphasised effect estimates and their confidence intervals rather than statistical significance alone.

Results

Participant characteristics and baseline comparison

Participant characteristics and primary outcome variables before the intervention are presented in Table 1.

Baseline body mass, squat 1RM, and relative 1RM were numerically lower in the VBT condition than in the PBT condition, with moderate-to-large standardised differences (Table 1). The largest standardised baseline difference was observed for squat 1RM (Hedges' $g = -0.94$, 95% $CI [-2.05, 0.22]$). Standardised differences for men-strike motion time, RFD0–100 ms, and the overlap index were smaller. All 95% confidence intervals were wide and included zero, indicating considerable uncertainty in the estimated between-condition differences.

Changes in squat 1RM

Changes in squat 1RM and body-mass-normalised relative 1RM before and after the intervention are presented in Table 2, with individual changes in relative 1RM shown in Figure 1A.

Squat 1RM increased in both conditions (VBT: 75.7 ± 22.8 to 112.9 ± 24.6 kg, $\Delta = 37.1 \pm 9.3$ kg; PBT: 97.0 ± 17.9 to 120.0 ± 19.0 kg, $\Delta = 23.0 \pm 5.7$ kg). The between-condition difference in change scores was 14.1 kg (95% $CI [4.5, 23.8]$; Hedges' $g = 1.62$, 95% $CI [0.32, 2.86]$).

Relative 1RM also increased in both conditions (VBT: 1.185 ± 0.153 to 1.838 ± 0.145 kg $\cdot$ kg⁻¹, $\Delta = 0.653 \pm 0.176$ kg $\cdot$ kg⁻¹; PBT: 1.329 ± 0.224 to 1.672 ± 0.196 kg $\cdot$ kg⁻¹, $\Delta = 0.344 \pm 0.084$ kg $\cdot$ kg⁻¹). The between-condition difference in change scores was 0.309 kg $\cdot$ kg⁻¹ (95% $CI [0.136, 0.482]$; Hedges' $g = 1.95$, 95% $CI [0.57, 3.27]$).

Changes in men-strike motion time

Changes in men-strike motion time before and after the intervention are presented in Figure 1B (individual changes) and Table 2.

Men-strike motion time changed from 0.681 ± 0.100 to 0.662 ± 0.060 s in the VBT condition ($\Delta = -0.019 \pm 0.047$ s) and from 0.697 ± 0.052 to 0.704 ± 0.055 s in the PBT condition ($\Delta = 0.007 \pm 0.096$ s). The between-condition difference in change scores was -0.025 s (95% $CI [-0.142, 0.092]$; Hedges' $g = -0.33$, 95% $CI [-1.39, 0.75]$). Both confidence intervals included zero, indicating considerable uncertainty in the estimated between-condition difference. Individual responses varied in both conditions (Figure 1B).

Changes in ground reaction force RFD during the push-off phase

Changes in push-off-phase RFD0–100 ms are presented in Figure 1C and Table 2. RFD0–100 ms changed from 87.81 ± 37.19 to 103.17 ± 49.32 N $\cdot$ kg⁻¹ $\cdot$ s⁻¹ in the VBT condition ($\Delta = 15.36 \pm 28.92$ N $\cdot$ kg⁻¹ $\cdot$ s⁻¹) and from 103.75 ± 66.68 to 91.49 ± 86.84 N $\cdot$ kg⁻¹ $\cdot$ s⁻¹ in

Table 1. Baseline participant characteristics and primary outcome variables before the training intervention.

Variable	VBT condition ($n = 7$) mean $\pm$ SD	PBT condition ($n = 5$) mean $\pm$ SD	Hedges' g	95% CI of g
Number (men/women)	3/4	3/2		
Body mass (kg)	63.1 ± 13.8	73.0 ± 7.1	-0.79	$[-1.89, 0.34]$
Squat 1RM (kg)	75.7 ± 22.8	97.0 ± 17.9	-0.94	$[-2.05, 0.22]$
Relative 1RM (kg $\cdot$ kg ⁻¹)	1.185 ± 0.153	1.329 ± 0.224	-0.71	$[-1.80, 0.41]$
Men-strike motion time (s)	0.681 ± 0.100	0.697 ± 0.052	-0.18	$[-1.24, 0.89]$
RFD0–100 ms (N $\cdot$ kg ⁻¹ $\cdot$ s ⁻¹)	87.81 ± 37.19	103.75 ± 66.68	-0.29	$[-1.35, 0.79]$
Overlap index (%)	12.4 ± 4.9	10.0 ± 5.2	0.43	$[-0.66, 1.49]$

VBT – velocity-based training, PBT – percentage-based training, 1RM – one-repetition maximum,

RFD – rate of force development

Hedges' g was calculated as VBT minus PBT; negative values indicate lower values in the VBT condition.

The 95% confidence intervals for Hedges' g were calculated using the noncentral t distribution.

Relative 1RM was calculated as 1RM divided by body mass.

The overlap index represents the percentage of time points during the normalised phase (0–95%) at which hip, knee, and ankle extension torques were simultaneously at or above 50% of their respective peak values.

Table 2. Changes in strength and biomechanical outcome variables before and after the training intervention

Variable	VBT pre (mean $\pm$ SD)	VBT post (mean $\pm$ SD)	VBT Δ (mean $\pm$ SD)	PBT pre (mean $\pm$ SD)	PBT post (mean $\pm$ SD)	PBT Δ (mean $\pm$ SD)	Δ difference (VBT-PBT)	95% CI of difference	Hedges' g [95% CI]
Squat 1RM (kg)	75.7 $\pm$ 22.8	112.9 $\pm$ 24.6	37.1 $\pm$ 9.3	97.0 $\pm$ 17.9	120.0 $\pm$ 19.0	23.0 $\pm$ 5.7	14.1	[4.5, 23.8]	1.62 [0.32, 2.86]
Relative 1RM (kg $\cdot$ kg ⁻¹)	1.185 $\pm$ 0.153	1.838 $\pm$ 0.145	0.653 $\pm$ 0.176	1.329 $\pm$ 0.224	1.672 $\pm$ 0.196	0.344 $\pm$ 0.084	0.309	[0.136, 0.482]	1.95 [0.57, 3.27]
Men-strike motion time (s)	0.681 $\pm$ 0.100	0.662 $\pm$ 0.060	-0.019 $\pm$ 0.047	0.697 $\pm$ 0.052	0.704 $\pm$ 0.055	0.007 $\pm$ 0.096	-0.025	[-0.142, 0.092]	-0.33 [-1.39, 0.75]
RFD0-100 ms (N $\cdot$ kg ⁻¹ $\cdot$ s ⁻¹)	87.81 $\pm$ 37.19	103.17 $\pm$ 49.32	15.36 $\pm$ 28.92	103.75 $\pm$ 66.68	91.49 $\pm$ 86.84	-12.26 $\pm$ 29.90	27.62	[-11.75, 66.98]	0.87 [-0.27, 1.97]
Overlap index (%)	12.4 $\pm$ 4.9	14.0 $\pm$ 4.2	1.6 $\pm$ 1.9	10.0 $\pm$ 5.2	10.0 $\pm$ 6.5	0.0 $\pm$ 5.3	1.6	[-4.8, 8.1]	0.42 [-0.67, 1.48]

VBT – velocity-based training, PBT – percentage-based training, 1RM – one-repetition maximum,

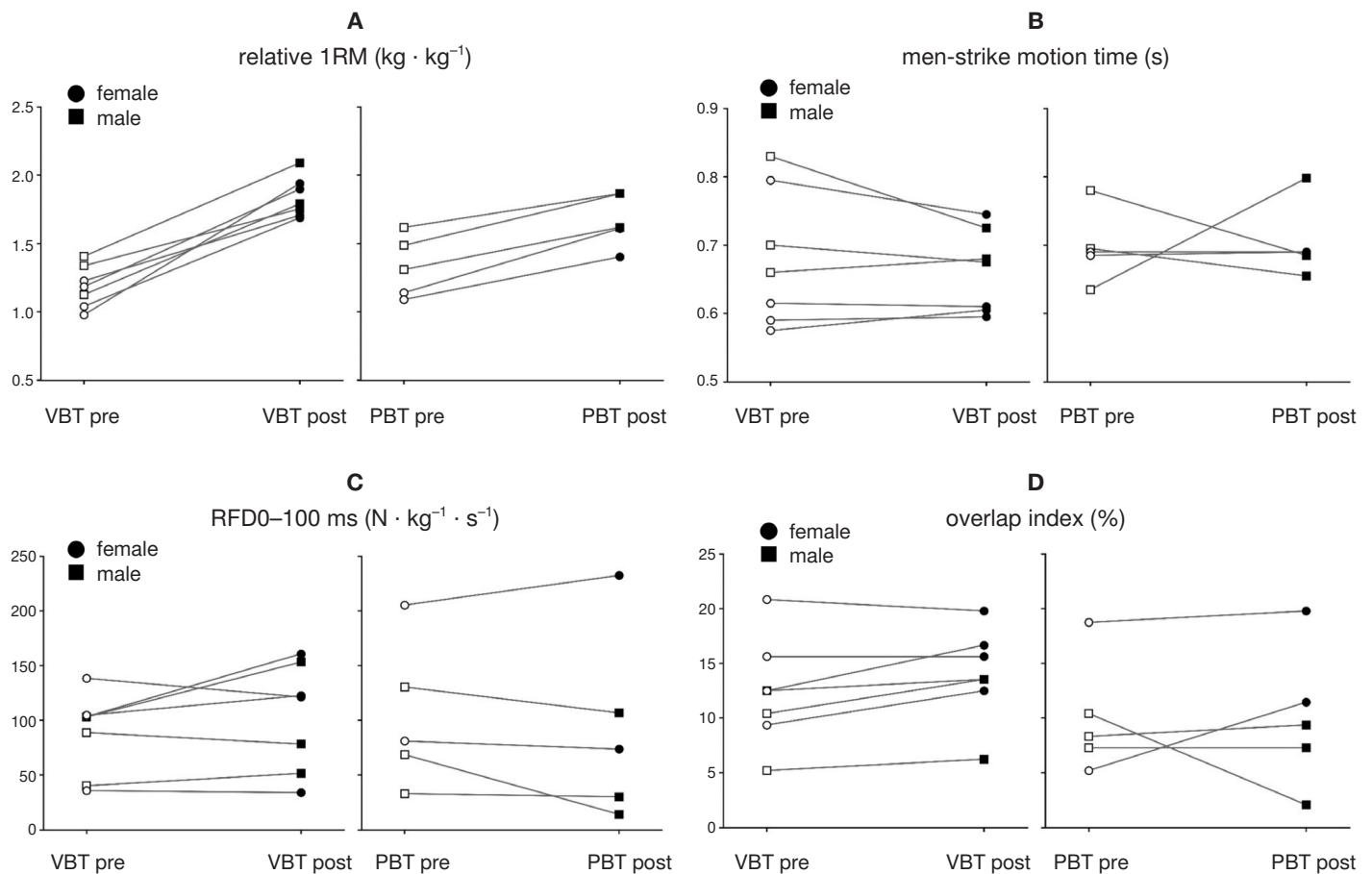
RFD – rate of force development, pre – before training, post – after training, Δ = post – pre

The between-condition difference was calculated as the VBT change minus the PBT change.

Hedges' g represents the standardised between-condition difference in change scores, with positive values indicating a numerically greater change in the VBT condition.

The corresponding 95% confidence intervals were calculated using the noncentral *t* distribution.

For men-strike motion time, a negative change indicates a shorter motion time.

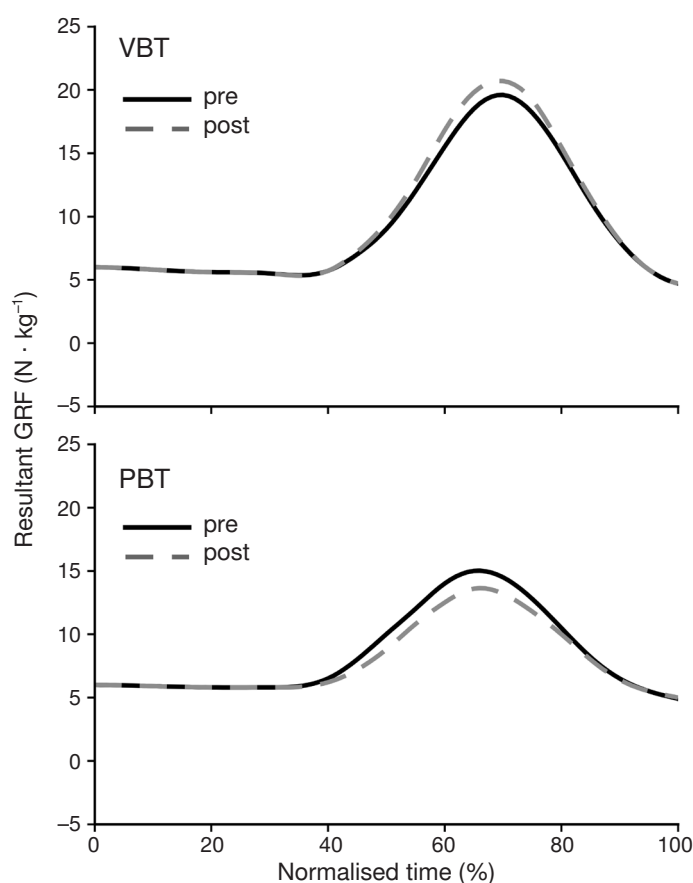


1RM – one-repetition maximum, RFD – rate of force development, VBT – velocity-based training, PBT – percentage-based training
pre – before training, post – after training

Figure 1. Individual pre-to-post changes in (A) relative one-repetition maximum (relative 1RM), (B) men-strike motion time, (C) push-off-phase rate of force development over 0–100 ms (RFD0–100 ms), and (D) overlap index. Each line represents one participant. Graphs show the velocity-based training (VBT) and percentage-based training (PBT) conditions separately. Circles represent female participants, and squares represent male participants.

the PBT condition ($\Delta = -12.26 \pm 29.90 \text{ N} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$). The between-condition difference in change scores was $27.62 \text{ N} \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$ (95% *CI* [-11.75, 66.98]; Hedges' $g = 0.87$, 95% *CI* [-0.27, 1.97]). Both confidence intervals included zero, indicating considerable uncertainty in the estimated between-condition difference. Individual responses varied in both conditions (Figure 1C).

Time-normalised waveforms of the resultant YZ-plane ground reaction force are presented in Figure 2. Visual inspection suggested a slightly greater early-phase increase after the intervention in the VBT condition. In the PBT condition, the post-intervention waveform was generally lower than the pre-intervention



GRF – ground reaction force, VBT – velocity-based training, PBT – percentage-based training, pre – before training, post – after training

Figure 2. Time-normalised waveforms of the resultant ground reaction force in the anteroposterior-vertical plane during the men-strike motion before (pre) and after (post) the training intervention. The velocity-based training (VBT) condition is shown in the upper graph and the percentage-based training (PBT) condition in the lower graph. Waveforms represent condition means based on the fastest successful trial selected for each participant and were normalised from movement onset (0%) to impact (100%).

waveform during the main force-rise phase. These waveform comparisons were descriptive and were not subjected to inferential time-series analysis.

Changes in the temporal overlap of high-torque phases (overlap index)

Changes in the overlap index before and after the intervention are presented in Figure 1D and Table 2.

The overlap index changed from $12.4 \pm 4.9\%$ to $14.0 \pm 4.2\%$ in the VBT condition ($\Delta = 1.6 \pm 1.9$ percentage points) and from $10.0 \pm 5.2\%$ to $10.0 \pm 6.5\%$ in the PBT condition ($\Delta = 0.0 \pm 5.3$ percentage points). The between-condition difference in change scores was 1.6 percentage points (95% *CI* [-4.8, 8.1]; Hedges' $g = 0.42$, 95% *CI* [-0.67, 1.48]). Both confidence intervals included zero, indicating considerable uncertainty in the estimated between-condition difference. Individual responses varied in both conditions (Figure 1D).

Descriptive time-series waveforms of lower-limb joint torque

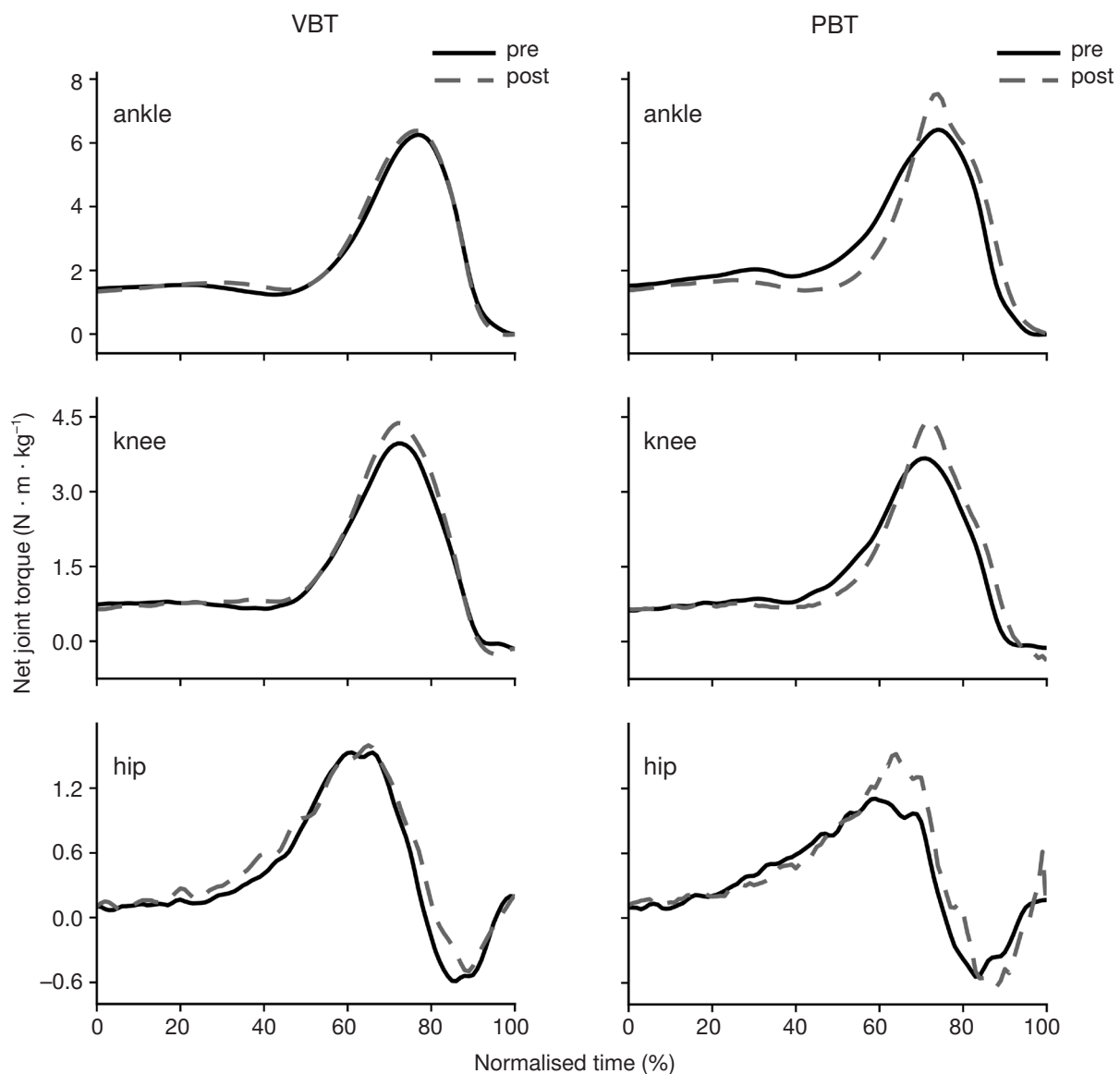
Time-normalised waveforms of ankle, knee, and hip extension torque are presented in Figure 3. In the VBT condition, the overall waveform profiles were broadly similar before and after the intervention, although post-intervention values appeared slightly higher around the principal peak, particularly for the ankle and knee joints.

In the PBT condition, post-intervention values also appeared higher around the principal peak for all three joints. These observations were descriptive, and no inferential time-series analysis was performed.

Reliability and sensitivity analyses

Reliability and sensitivity results are presented in Supplementary Tables S1–S4. RFD0–100 ms showed higher single-trial reliability than RFD0–50 ms, and three-trial averages were more reliable than single trials. For the overlap index at the 50% threshold, reliability was also higher for the mean of three trials.

Analyses based on the mean of all valid trials produced results similar to the primary analysis. Hedges' g was 1.02 (95% *CI* [-0.15, 2.15]) for RFD0–100 ms and 0.31 (95% *CI* [-0.77, 1.37]) for the overlap index (Supplementary Table S2). Results for the overlap index were also similar across the 40%, 50%, and 60% thresholds, with all confidence intervals including zero (Supplementary Table S3).



VBT – velocity-based training, PBT – percentage-based training, pre – before training, post – after training

Figure 3. Time-normalised waveforms of ankle, knee, and hip extension torques during the men-strike motion before (pre) and after (post) the training intervention. Graphs are arranged from top to bottom as ankle, knee, and hip joints and from left to right as the velocity-based training (VBT) and percentage-based training (PBT) conditions. Waveforms represent condition means based on the fastest successful trial selected for each participant and were normalised from movement onset (0%) to impact (100%).

Exploratory baseline-adjusted analyses favoured the VBT condition for absolute 1RM (adjusted difference = 14.2 kg, 95% CI [2.2, 26.1]) and relative 1RM ($0.251 \text{ kg} \cdot \text{kg}^{-1}$, 95% CI [0.031, 0.471]). Adjusted differences for RFD0–100 ms and the overlap index remained uncertain. For men-strike motion time, the condition-by-baseline interaction indicated that the homogeneity-of-regression-slopes assumption was not supported ($p = 0.010$); therefore, the common-slope adjusted estimate should be interpreted cautiously (Supplementary Table S4).

Discussion

Principal findings and cautious interpretation

This exploratory study compared changes in squat strength and kendo men-strike biomechanics between two resistance-training conditions. Absolute and relative squat 1RM increased more in the VBT condition. The point estimate for RFD0–100 ms also favoured VBT, and a similar estimate was obtained when all valid trials were averaged; however, the confidence intervals were wide and included zero. Between-condition dif-

ferences in men-strike motion time and the overlap index were smaller and similarly uncertain. Overall, the clearest differences concerned squat strength, whereas evidence for changes in kendo-specific biomechanical outcomes was limited.

Interpretation is constrained by the non-random allocation. Academic year was completely confounded with intervention condition, baseline strength was lower in the VBT condition, and the interventions differed in load prescription and progression. The findings therefore represent an exploratory comparison of two training conditions and cannot be attributed to velocity feedback alone.

Strength gains, baseline differences, and possible pre-test underestimation

The larger increases in absolute and relative squat 1RM in the VBT condition should be considered alongside the baseline imbalance. Participants in this condition began with lower strength, which may have provided greater scope for improvement and increased susceptibility to regression toward the mean. Baseline-adjusted estimates also favoured VBT, but the adjustment could not separate intervention effects from academic year or other unmeasured cohort differences.

The approximately 49% increase in squat 1RM over seven weeks is unlikely to reflect muscular adaptation alone. Several participants had limited experience with structured back-squat training, and the initial test may have underestimated their maximal capacity. Repeated exposure may have improved technique, depth consistency, trunk control, confidence under heavy loads, and the ability to express maximal effort. Short-term strength gains may also reflect neural and muscular adaptations, with pre-training strength contributing to individual variation in training response [17]. The observed increase probably reflected both physiological adaptation and test-specific learning.

Training prescription may also have contributed to the difference between conditions. In the VBT condition, load was adjusted according to repetition velocity, whereas the PBT condition used the same absolute load throughout the intervention. As strength increased, the relative intensity of the PBT load may therefore have declined. Previous VBT-PBT comparisons have used planned progression in both conditions and individualised velocity profiles to adjust the load [18]. In the present study, the larger strength gain may reflect load progression, autoregulation, and maintenance of relative intensity, in addition to real-time velocity feedback.

Push-off RFD and limited transfer to men-strike motion time

The point estimate for RFD0–100 ms favoured the VBT condition and was similar when the mean of all valid trials was analysed. RFD0–100 ms also showed better trial-to-trial reliability than RFD0–50 ms. Thus, the result was not solely dependent on the selection of the fastest successful trial. Nevertheless, the confidence interval was wide and included zero, and the result does not provide conclusive evidence that VBT improved push-off RFD.

RFD0–100 ms represented the early increase in the resultant ground reaction force during push-off. Rapid propulsive force is also important in other movements requiring forward whole-body acceleration. In fencing, rear-leg propulsion and lower-limb power contribute to lunge performance [19], whereas sprint-start performance is related to horizontal block force and lower-limb joint kinetics [20]. Although these tasks differ from the kendo men-strike, they illustrate the relevance of rapid lower-limb force production. Direct comparison remains limited because the present RFD measure used a task-specific reference point rather than a conventional contraction-onset definition.

Resistance training performed with maximal intended velocity can improve rapid force production, particularly when training and testing share relevant mechanical characteristics [3, 4]. Both conditions used maximal concentric intent, while VBT also included velocity feedback and load autoregulation. The RFD estimate may therefore reflect several intervention features as well as baseline and cohort differences. Transfer was also limited by mechanical differences between the squat and the kendo push-off in posture, support condition, movement direction, and technical demand.

Men-strike motion time showed only a small and uncertain between-condition difference. This agrees with reports that increases in squat or hip-thrust strength do not necessarily improve sprint or jump performance [21, 22]. Men-strike time depends on push-off force as well as whole-body COM displacement, front-leg motion, trunk and upper-limb movement, shinai control, and their timing. The present findings therefore suggest, at most, a possible difference in one component of push-off force production rather than improved overall striking performance.

Temporal overlap of high-torque phases and interpretation of the overlap index

The overlap-index estimate was modest and imprecise. Analyses using thresholds of 40%, 50%, and

60%, as well as the mean of all valid trials, produced estimates in the same general direction, but all confidence intervals included zero. The result was therefore not strongly dependent on the threshold or trial-selection procedure, but provides limited evidence of an intervention-related change.

Reliability was higher for the mean of three trials than for a single trial, particularly after the intervention. Multiple-trial averaging may therefore provide a more stable estimate. However, reliability reflects reproducibility and does not establish the validity of the index as a measure of coordination.

Previous kendo research has described relatively simultaneous torque generation among the ankle, knee, and hip during push-off [1, 2]. In contrast, effective performance in vertical jumping may involve a proximal-to-distal sequence that varies with task demands [23]. Improved countermovement-jump performance with an arm swing has also been associated with a greater delay between proximal and distal joint extension rather than greater simultaneity [24]. Effective coordination may therefore involve either overlapping or sequential joint contributions.

A higher overlap index should not automatically be interpreted as better coordination. The index quantifies only the proportion of time during which all three extension torques exceed a defined percentage of their respective peaks. It does not describe peak order, joint power, mechanical work, energy transfer, or motion outside the sagittal plane. The waveform comparisons were also descriptive. The overlap index should therefore be regarded as an exploratory descriptor of high-torque temporal overlap rather than a validated global measure of lower-limb coordination.

Practical implications

Both conditions increased squat 1RM, indicating that structured back-squat training may improve maximal squat strength in university kendo athletes. Velocity monitoring and session-by-session load adjustment may offer a practical method for adapting training load as strength and readiness change. Feedback may also help athletes maintain maximal concentric intent while reducing reliance on frequent 1RM testing.

These findings do not establish the general superiority of VBT over PBT. The PBT condition used a fixed absolute load based on the pre-intervention 1RM and did not include planned progression or periodic strength reassessment. This protocol illustrates a practical limitation that can arise when percentage-based training is implemented without such adjustments: as strength

increases, the prescribed absolute load represents a lower relative intensity. This is, however, not an inherent limitation of percentage-based training, because periodic 1RM reassessment or planned load progression can be used to maintain the intended relative intensity. The present comparison therefore suggests a possible operational advantage of velocity-guided autoregulation but does not show that velocity feedback is superior to a well-progressed percentage-based program.

For kendo, resistance training with maximal intended velocity may complement technical practice aimed at rapid push-off force production. However, increased squat strength or RFD should not be expected to translate automatically into faster striking. Resistance training should be combined with task-specific work on footwork, whole-body propulsion, upper-body and shinai control, and movement timing. The overlap index remains a research measure rather than a validated coaching tool.

Limitations and future directions

Several study limitations should be considered. First, participants were allocated according to academic year rather than randomly, and academic year was completely confounded with intervention condition. Differences in age, kendo and resistance-training experience, squat familiarity, baseline strength, and responsiveness to training may have affected the results. Baseline adjustment could not remove these cohort differences, and duplicate baseline 1RM tests were not conducted. Initial strength may therefore have been underestimated in participants with limited squat experience.

Second, the interventions differed beyond velocity feedback. Load was autoregulated in the VBT condition but remained fixed in the PBT condition, and the number of sets could differ. Complete session-level records of actual training loads and mean concentric velocities were unavailable for three of the seven VBT participants. The available records were therefore not considered representative of the entire condition and were not summarised as group-level training exposure. Consequently, the observed differences may reflect load progression, relative intensity, autoregulation, or training exposure rather than velocity feedback alone.

Third, the small sample produced imprecise estimates and prevented sex-stratified analyses. Because the overlap index was normalised to each joint's own peak torque and expressed as a proportion of normalised movement time, sex-related differences in absolute torque magnitude would not directly determine

the index. However, differences in torque-waveform shape, peak timing, and movement strategy could still affect the overlap index. Participants were drawn from one university club, which limits generalisability of findings. The primary analysis also used the fastest successful trial. Although analyses based on all valid trials produced similar estimates, three-trial averages were generally more reliable and should be prioritised in future studies.

Fourth, several measurement limitations apply as well. The overlap index has not been validated as a global measure of coordination, inverse dynamics were limited to the sagittal plane, and the final 5% of the motion was excluded after the push-off foot left the force plate. Excluding the final 5% may also have obscured terminal acceleration and joint-torque characteristics immediately before impact; however, inverse-dynamics estimates during this period were considered unreliable because the push-off foot had begun to leave the force plate. Filtering ground reaction force at 10 Hz may have attenuated rapid force changes, particularly for RFD0–50 ms, and the task-specific RFD reference point limits comparison with conventional RFD measures. The experimental strike was self-initiated, directed at a fixed target, and performed without armour or an opponent, and therefore did not reproduce the perceptual and tactical demands of competition.

Future studies should use randomised or baseline-matched designs, equivalent load progression, repeated baseline testing, complete training records, larger samples, and multiple-trial biomechanical outcomes. More representative striking tasks and further validation of the overlap index are also required.

Conclusions

In this exploratory non-randomised study of university kendo athletes, squat 1RM increased in both training conditions, with larger increases found in absolute and relative 1RM in the VBT condition. The point estimate for RFD0–100 ms also favoured the VBT condition, but the 95% confidence interval was wide and included zero. Between-condition differences in men-strike motion time and the temporal overlap of high-torque phases among the lower-limb joints were small and uncertain. Thus, the clearest finding concerned maximal squat strength, whereas evidence for changes in kendo-specific biomechanical outcomes remained limited.

Because academic year was completely confounded with intervention condition, baseline squat strength was lower in the VBT condition, and the interventions

differed in load progression and autoregulation, the findings cannot be attributed to velocity feedback alone. The velocity-guided, autoregulated approach used in this study may be useful for supporting squat-strength development, but evidence of transfer to push-off force production or faster men-strike performance remains inconclusive. Randomised or baseline-matched studies with equivalent load progression, larger samples, and multiple-trial biomechanical outcomes are therefore recommended.

Ethical approval

The research involving human participants complied with all relevant national regulations and institutional policies, followed the principles of the Declaration of Helsinki, and was approved by the Ethics Committee of Chukyo University (approval No. 2025-036).

Informed consent

All participants received a detailed explanation of the purpose and procedures of the study, the voluntary nature of participation, and the handling of personal information. Written informed consent was obtained from all participants before participation.

Conflict of interest

The authors state no conflict of interest.

Disclosure statement

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Supplementary materials

Table S1. Trial-to-trial reliability of RFD and the overlap index

Outcome	Time point	<i>n</i>	<i>ICC</i> (3,1)	<i>ICC</i> (3, <i>k</i>)	Typical error	<i>TE</i> /mean (%)	Mean within-subject <i>CV</i> (%)
RFD 0–50 ms	pre	11	0.659	0.853	28.62 N · kg ⁻¹ · s ⁻¹	60.0	55.9
RFD 0–50 ms	post	11	0.644	0.844	21.62 N · kg ⁻¹ · s ⁻¹	40.5	35.0
RFD 0–100 ms	pre	11	0.816	0.930	21.74 N · kg ⁻¹ · s ⁻¹	27.5	39.0
RFD 0–100 ms	post	11	0.841	0.941	20.20 N · kg ⁻¹ · s ⁻¹	21.8	27.1
Overlap index, 40% threshold	pre	12	0.879	0.956	1.67 pp	11.0	10.6
Overlap index, 40% threshold	post	11	0.651	0.848	3.18 pp	19.2	17.3
Overlap index, 50% threshold	pre	12	0.912	0.969	1.27 pp	10.6	11.1
Overlap index, 50% threshold	post	11	0.730	0.890	2.42 pp	17.9	18.4
Overlap index, 60% threshold	pre	12	0.857	0.947	1.44 pp	15.5	18.0
Overlap index, 60% threshold	post	11	0.681	0.865	2.56 pp	25.0	23.9

RFD – rate of force development, *ICC* – intraclass correlation coefficient, *TE* – typical error – *MSE* – mean square error, *CV* – coefficient of variation, pre – before training, post – after training, *n* – number of participant-by-time-point cells, pp – percentage points

ICC(3,1) and *ICC*(3,*k*), with *k* = 3, denote two-way mixed-effects consistency coefficients for a single trial and the mean of three trials, respectively. Typical error (*TE*) = $\sqrt{\text{MSE}}$. Reliability analyses used complete three-trial cells: RFD pre and post, *n* = 11; overlap index pre, *n* = 12; overlap index post, *n* = 11.

Table S2. Sensitivity of RFD and overlap-index results to trial selection

Outcome	Trial selection	VBT pre (mean ± <i>SD</i>)	VBT post (mean ± <i>SD</i>)	VBT Δ (mean ± <i>SD</i>)	PBT pre (mean ± <i>SD</i>)	PBT post (mean ± <i>SD</i>)	PBT Δ (mean ± <i>SD</i>)	Δ difference (VBT – PBT) [95% <i>CI</i>]	Hedges' <i>g</i> [95% <i>CI</i>]
RFD 0–50 ms	fastest successful trial	44.30 ± 21.85	62.66 ± 31.60	18.36 ± 23.61	92.21 ± 103.25	62.77 ± 79.08	–29.45 ± 28.18	47.81 [11.98, 83.64]	1.73 [0.40, 3.00]
RFD 0–50 ms	mean of all valid trials	33.67 ± 20.23	50.26 ± 19.70	16.59 ± 17.50	59.98 ± 61.95	49.51 ± 48.13	–10.46 ± 14.64	27.05 [6.21, 47.89]	1.52 [0.25, 2.74]
RFD 0–100 ms	fastest successful trial	87.81 ± 37.19	103.17 ± 49.32	15.36 ± 28.92	103.75 ± 66.68	91.49 ± 86.84	–12.26 ± 29.90	27.62 [–11.75, 66.98]	0.87 [–0.27, 1.97]
RFD 0–100 ms	mean of all valid trials	67.97 ± 38.69	89.32 ± 39.06	21.36 ± 27.88	87.46 ± 58.56	84.02 ± 66.62	–3.45 ± 9.41	24.80 [–1.50, 51.11]	1.02 [–0.15, 2.15]
Overlap index, 50% threshold	fastest successful trial	12.35 ± 4.94	13.99 ± 4.20	1.64 ± 1.89	10.00 ± 5.24	10.00 ± 6.49	–0.00 ± 5.26	1.64 [–4.79, 8.06]	0.42 [–0.67, 1.48]
Overlap index, 50% threshold	mean of all valid trials	12.75 ± 4.38	14.43 ± 3.16	1.69 ± 2.34	11.04 ± 4.13	11.84 ± 5.00	0.80 ± 3.09	0.89 [–2.97, 4.75]	0.31 [–0.77, 1.37]

VBT – velocity-based training, PBT – percentage-based training, pre – before training, post – after training, RFD – rate of force development, *CI* – confidence interval, Δ = post – pre

Hedges' *g* represents the standardised between-condition difference in change scores (VBT – PBT). The mean-of-all-valid-trials analysis included two valid RFD trials at both pre and post for one PBT participant and two valid overlap-index trials at Post for the same participant; all other participant-by-time-point cells contained three valid trials. VBT, *n* = 7; PBT, *n* = 5.

Table S3. Sensitivity of the overlap index to the torque threshold

Threshold	VBT pre (mean $\pm$ SD)	VBT post (mean $\pm$ SD)	VBT Δ (mean $\pm$ SD)	PBT pre (mean $\pm$ SD)	PBT post (mean $\pm$ SD)	PBT Δ (mean $\pm$ SD)	Δ difference (VBT – PBT) [95% CI]	Hedges' g [95% CI]
40% of each joint peak	15.87 $\pm$ 4.76	17.76 $\pm$ 3.87	1.88 $\pm$ 2.78	14.10 $\pm$ 4.69	15.31 $\pm$ 5.42	1.22 $\pm$ 4.25	0.67 [–4.56, 5.90]	0.18 [–0.89, 1.24]
50% of each joint peak	12.75 $\pm$ 4.38	14.43 $\pm$ 3.16	1.69 $\pm$ 2.34	11.04 $\pm$ 4.13	11.84 $\pm$ 5.00	0.80 $\pm$ 3.09	0.89 [–2.97, 4.75]	0.31 [–0.77, 1.37]
60% of each joint peak	9.82 $\pm$ 3.90	10.86 $\pm$ 3.54	1.04 $\pm$ 2.10	8.47 $\pm$ 3.46	9.17 $\pm$ 4.42	0.69 $\pm$ 2.77	0.35 [–3.11, 3.81]	0.13 [–0.93, 1.19]

VBT – velocity-based training, PBT – percentage-based training, pre – before training, post – after training, CI – confidence interval, Δ = post – pre

Values are based on the mean of all valid trials. The analysis interval was fixed at 0–95% of the movement; only the threshold used to define high joint-torque phases was changed. The 50% threshold was used in the primary analysis.

Overlap-index values are expressed as percentages, and changes are expressed in percentage points.

Table S4. Exploratory baseline-adjusted comparisons of post-intervention outcomes

Outcome	Pooled mean baseline value	Adjusted VBT post	Adjusted PBT post	Adjusted difference (VBT – PBT)	HC3 robust 95% CI	HC3 robust p	Condition $\times$ baseline p
Squat 1RM (kg)	84.6	121.7	107.6	14.2	[2.2, 26.1]	0.025	0.951
Relative 1RM (kg $\cdot$ kg ^{–1})	1.245	1.874	1.622	0.251	[0.031, 0.471]	0.029	0.283
Men-strike motion time (s)	0.688	0.665	0.700	–0.035	[–0.127, 0.057]	0.409	0.010
RFD0–100 ms (N $\cdot$ kg ^{–1} $\cdot$ s ^{–1})	94.45	111.09	80.40	30.70	[–17.68, 79.08]	0.185	0.686
Overlap index (%)	11.37	13.23	11.07	2.16	[–4.74, 9.06]	0.497	0.958

VBT – velocity-based training, PBT – percentage-based training, 1RM – one-repetition maximum, RFD – rate of force development, HC3 – heteroskedasticity-consistent covariance estimator (type 3), pre – before training, post – after training, CI – confidence interval

Adjusted means were estimated at the pooled mean baseline value using the model post = intercept + condition + pre, with VBT coded as 1 and PBT as 0. Confidence intervals and p values were based on HC3 heteroskedasticity-robust standard errors. The condition $\times$ baseline interaction was examined as a diagnostic of the homogeneity-of-regression-slopes assumption. This assumption was not supported for men-strike motion time ($p = 0.010$); therefore, its common-slope adjusted estimate should be interpreted cautiously.

Because academic year was completely aligned with intervention condition, this analysis adjusts only for the measured baseline value and cannot separate the effects of academic year, training experience, or other unmeasured cohort differences from the intervention condition. Therefore, these results are exploratory and do not establish a causal effect of VBT.