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Skill level influences kinematic strategies for regulating ball velocity during overhand throwing

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ABSTRACT

Purpose. Overhand throwing is a fundamental motor skill in which velocity regulation is crucial for accuracy. While maximal-effort throwing has been extensively studied, how skill level affects the kinematic strategies used to regulate submaximal velocities remains less well understood. This study aimed to compare movement strategies for modulating throwing velocity between eight skilled baseball pitchers (19.4 ± 0.9 years) and ten non-skilled young males (22.7 ± 1.2 years) throwing a baseball at intensities of 20%, 40%, 60%, 80%, and 100% of their maximal ball velocity.

Methods. We used three-dimensional motion analysis to compare the angular velocity in the upper torso and shoulder, elbow, and wrist joints during the ascending (AP) and descending (DP) phases of ball acceleration.

Results. The maximal ball velocity was higher in the skilled group (33.1 ± 1.9 m/s) than in the non-skilled group (24.9 ± 4.0 m/s, $p < 0.001$). The skilled group generated a greater proportion of the final ball velocity during the AP of ball acceleration (~ 80%) than the non-skilled group (~ 65%). This was accompanied by higher maximum angular velocities of wrist palmar flexion, elbow extension, and shoulder internal rotation. In the subsequent DP of ball acceleration, the skilled group employed a distinct strategy, showing shoulder horizontal abduction and attenuated upper torso rotation to augment shoulder internal rotation velocity prior to ball release. In contrast, the non-skilled group used shoulder horizontal adduction and continued to accelerate the upper torso.

Conclusions. These findings indicate that, depending on overhand throwing skill level, ball velocity is modulated by specific coordination strategies rather than simply by variation in effort.

Key words: overhand throwing, kinematics, velocity regulation, skill level, joint angular velocity

Introduction

Overhand ball throwing is a fundamental motor skill used in a wide variety of activities, from daily tasks and recreational games to competitive sports. Ball velocity and accuracy are important components of overarm throwing performance [1]. Maximal ball velocity is a key indicator of throwing performance, as it directly influences throwing distance [2]. For example, Gorostiaga *et al.* [3] reported that elite handball players achieve higher maximal ball velocities than amateurs, while Melchiorri *et al.* [4] quantified throwing velocity in elite water polo players and found that only for the goalkeeper position was the ball speed significantly lower than for the other positions. Similarly, Toffan *et al.* [5] found that maximal ball velocity is a strong predictor of throwing performance in high school American football quarterbacks.

Many studies have examined the kinematic differences in maximal-effort throwing across different skill levels. Skilled throwers exhibit distinct movement patterns that achieve high ball velocity. For instance, rotation angular velocities in the dominant upper arm and trunk correlate with elbow extension angular velocity during maximal-effort throws [6, 7]. Additionally, rotational velocities of the pelvis and upper torso affect ball velocity at the moment of release [8–10]. However, throwers do not always throw with maximal effort, and submaximal throwing is common in competitive contexts in which throwing velocity must be

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graded to the demands of the situation. For example, baseball pitchers vary ball velocity to throw different pitch types (*e.g.*, breaking balls), and fielders adjust their throws according to the distance to the target [11].

Several studies have compared how throwers kinematically and kinetically regulate throws at different ball velocities, including submaximal efforts. Hirashima *et al.* [12] analysed angular velocities, muscle torque, and interaction torque in the wrist, elbow, and shoulder joints during slow, medium, and fast throws. Their results indicated that throwers adjust muscle torque and interaction torque to increase elbow and shoulder extension angular velocity at ball release while maintaining wrist palmar flexion angular velocity [12]. In another study, Hirashima *et al.* [13] reported that skilled throwers adjust muscle torque and interaction torque to increase both elbow and shoulder extension angular velocity and wrist palmar flexion angular velocity at ball release. This discrepancy may reflect differences in experimental conditions (*i.e.*, Hirashima *et al.* [12] used a sitting position, while Hirashima *et al.* [13] examined baseball pitching from a standing position). Furthermore, in Hirashima *et al.* [13], the "fast" condition was maximal effort, "slow" was a non-standardised slow motion, and "medium" was an intermediate effort, which means the relative effort for slow and medium velocities was not standardised across participants. In contrast, Urata *et al.* [14] examined kinematics in non-skilled throwers during baseball pitching with standardised relative efforts ranging from 20% to 100% of their maximal ball velocity. They found that angular velocity in wrist palmar flexion, elbow extension, shoulder internal rotation, and upper torso left rotation increased with target ball velocity [14]. Urbin *et al.* [15] compared skilled and non-skilled throwers across a range of relative velocities (40–100% of maximum) from the perspective of impulse-variability theory, a motor-control account of how force output is scaled across levels of effort. However, they focused on the variability of throwing velocity rather than on the kinematic strategies used to regulate it. Thus, how skilled and non-skilled throwers kinematically regulate ball velocity under matched relative efforts remains unclear.

Based on findings from maximal-effort studies [6–10], it is plausible that throwing strategies for submaximal efforts also differ by skill level. While Hirashima *et al.* [13] included skilled participants, they did not control for relative effort across individuals. Conversely, Urata *et al.* [14] controlled for relative effort but only included non-skilled throwers. Therefore, the present study aimed to clarify the fundamental differences in movement strategies for regulating ball velocity by systematically comparing skilled and non-skilled throwers under matched relative effort conditions. We hypothesised that movement strategies for regulating relative ball velocity would differ between skill levels.

Material and methods

Participants

Eight well-trained young male baseball pitchers (skilled group; 7 right-handed, 1 left-handed; age: 19.4 ± 0.9 years, height: 178.2 ± 4.3 cm, body mass: 74.1 ± 5.5 kg, baseball experience: 10.8 ± 3.2 years) and 10 right-handed young males without baseball experience (non-skilled group; age: 22.7 ± 1.2 years, height: 172.7 ± 5.1 cm, body mass: 68.5 ± 10.2 kg) participated in this study. All participants were informed of the experimental procedure and provided written informed consent in accordance with the Declaration of Helsinki. The data for all 10 non-skilled participants were previously published in Urata *et al.* [14] and were used in this study with permission from the authors. Only the ball-velocity and joint angular-velocity data of this group were re-analysed here, using the same procedures applied to the skilled group. All analyses reported in the present study, including the decomposition of the ball acceleration phase into ascending and descending sub-phases and the comparison between skill levels, are novel. Both groups were measured with the same motion capture system, laboratory set-up, and experimental protocol. The non-skilled group was measured in 2010 and the skilled group in 2012. Although the two groups were measured approximately two years apart, the positioning error of this type of system (mean absolute error < 2 mm [16]; see Data recording) is negligible relative to the between-group differences observed here, so instrumentation-related variability is unlikely to account for the present findings.

Experimental procedure

After a self-selected warm-up, participants threw a baseball (diameter: 72 mm, mass: 145 g, 1BJBH105 001P, Mizuno Corporation, Osaka, Japan) at a 1 m × 1 m square target. The centre of the target was positioned 1 m above the ground. For the right-handed participants, the target was positioned 2 m to the left of their starting position. For the left-handed participants, the target was placed 2 m to the right of their starting position. The starting position was lateral to the target. First, we evaluated each participant's maximal ball velocity and then calculated four target ball velocities

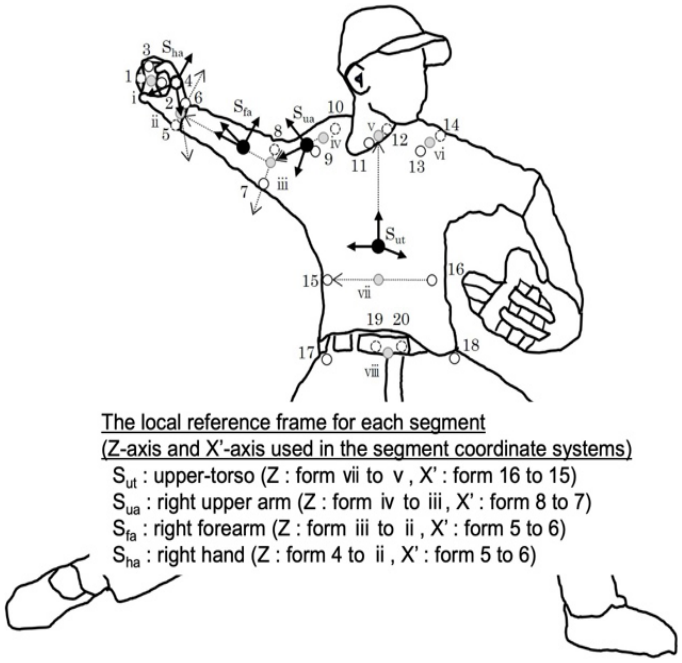
corresponding to 20%, 40%, 60%, and 80% of their maximal ball velocity. Before starting experimental trials, participants performed three practice throws at each target ball velocity while receiving real-time verbal feedback on their resultant ball velocity from a technician. Informal piloting suggested that a random presentation order tended to increase the number of trials required, and we therefore adopted a blocked order. Thus, to minimise the participants' burden, trials were performed in blocks in the order of 80%, 60%, 40%, and 20% of maximal ball velocity, with a 5-minute rest period between blocks. A successful trial was defined as a resultant ball velocity within ± 5% of the target ball velocity. Each block was completed after two successful trials. Of the successful trials, the one closest to the target velocity for each condition was selected.

Data recording

We recorded the positions of 20 spherical reflective markers (diameter: 9 mm) using a 10-camera motion capture system (Vicon Nexus-VICON T10, Vicon Motion Systems, Oxford, UK) operating at 250 Hz [16]. A dynamic wand calibration was performed before each participant was measured. The markers were attached to participants' bodies and the ball (see Figure 1). A right-hand-system global reference frame was fixed on the ground, with the *X*-axis perpendicular to the throwing direction, the *Y*-axis aligned with the throwing direction, and the *Z*-axis oriented vertically. For the left-handed participants, the same calculations were performed with the *X*-axis in the opposite direction. The position data, calculated relative to the global reference frame, were smoothed using a fourth-order Butterworth low-pass digital filter. The optimal cut-off frequency was determined for each marker and trial using the residual analysis method described by Winter [17], which yielded cut-off frequencies ranging from 20 to 23 Hz.

Data analysis

The participant's upper body was modelled with four segments: the upper torso, the upper arm, the forearm, and the hand with the ball. Figure 1 illustrates the locations of the local reference frame and the segment reference: the upper torso (S_{ut}), the upper arm (S_{ua}), the forearm (S_{fa}), and the hand with the ball (S_{ha}). The local reference frames for each joint were named J_{sh} (shoulder), J_{el} (elbow), and J_{wr} (wrist). Shoulder joint motion was defined as the motion of the upper arm relative to the upper torso, the elbow joint motion as the motion of the forearm relative to the upper arm, and the wrist joint motion as the motion of the hand relative to the forearm. The shoulder joint reference frame (J_{sh}) defined the *X*-axis as horizontal adduction (+)/abduc-



The experimental set-up for the right-handed throwers is shown, detailing the positions of 20 spherical reflective markers (open circles) used to track the motion of the ball and body segments. The local coordinate system for the upper torso (S_{ut}), upper arm (S_{ua}), forearm (S_{fa}), and right hand (S_{ha}) was defined using these markers. Calculated coordinate points (grey circles), such as the centre of the ball (cb) and joint centres (rw, re, rs), were derived from the marker positions for use in the analysis.

Figure 1. Kinematic model and marker set for the three-dimensional motion analysis

tion (–), the *Y*-axis as adduction (+)/abduction (–), and the *Z*-axis as internal (+)/external (–) rotation. The elbow joint reference frame (J_{el}) defined the *X*-axis as varus (+)/valgus (–), the *Y*-axis as extension (+)/flexion (–), and the *Z*-axis as pronation (+)/supination (–). The wrist joint reference frame (J_{wr}) defined the *X*-axis as palmar flexion (+)/dorsal flexion (–), the *Y*-axis as ulnar (+)/radial (–) flexion, and the *Z*-axis as pronation (+)/supination (–).

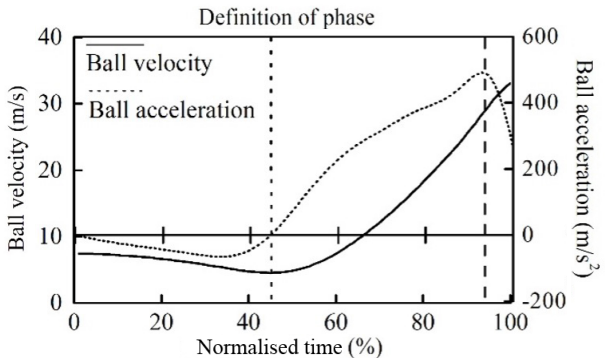
We calculated segment angular velocity vectors by the temporal differentiation and cross-product of orthogonal unit vectors (i_i, j_i, and k_i) according to the following equations [18]:

$$\omega_{ix} = k_i \cdot \frac{dj_i}{dt}, \omega_{iy} = i_i \cdot \frac{dk_i}{dt}, \omega_{iz} = j_i \cdot \frac{di_i}{dt}$$

where: ω_i is the angular velocity vector of segment i. Joint angular velocity vectors (rad/s) were computed from the segment angular velocity vectors. The segment angular velocity vector was transformed from its local reference frame to the global reference frame using the following rotation matrix:

$$\begin{bmatrix} \omega'_{ix} \\ \omega'_{iy} \\ \omega'_{iz} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \omega_{ix} \\ \omega_{iy} \\ \omega_{iz} \end{bmatrix}$$

where: ω_{ix}, ω_{iy}, and ω_{iz} indicate the *X*-, *Y*-, and *Z*-axis components of the segment *i* angular velocity vector in the global reference frame. Other segment angular velocity vectors were transformed to the global reference frame using a similar rotation matrix for each segment. The direction of the relative angular velocity vector was defined from the distal to the proximal segment.



A representative trace of ball velocity (solid line) and ball acceleration (dotted line) is plotted against a normalised time course from the point of maximal take-back (0%) to ball release (100%). The throwing motion was divided into two phases based on the acceleration profile: an ascending phase and a descending phase. The ascending phase is defined as the period from the onset of positive ball acceleration (vertical short-dashed line) to the point of maximum ball acceleration. The descending phase begins at maximum ball acceleration (vertical long-dashed line) and ends at ball release.

Figure 2. Definition of the throwing phases based on ball kinematics

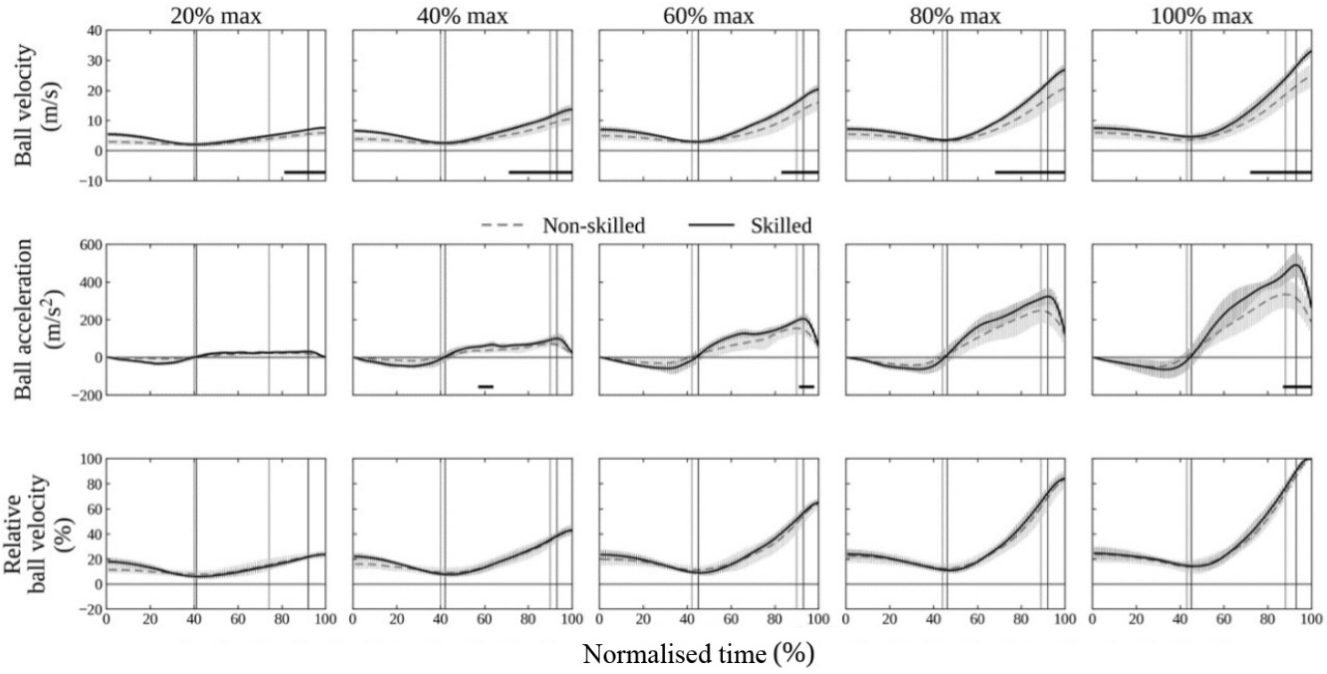
The analysed interval of the throwing motion extended from the point of maximal take-back to ball release. We calculated absolute and relative ball velocities, joint angular velocities, and the absolute and relative time required for the throwing motion. Relative time was defined as a percentage, from 0% (maximal take-back) to 100% (ball release). The ball acceleration phase was divided into an ascending phase (from the zero crossing to the peak of ball acceleration) and a descending phase (from the peak of ball acceleration to ball release; see Figure 2). To quantify the changes during the throwing phases, we also computed the delta values (maximum minus minimum) of absolute and relative ball velocity in both the ascending and descending phases of ball acceleration.

Statistical analysis

Group differences in the time-series of absolute ball velocity, ball acceleration, and relative ball velocity (Figure 3) were tested using one-dimensional statistical parametric mapping (SPM). Each series was normalised to 100 points and compared at every node with a two-sample *t*-test using the spm1d package (version 0.4, www.spm1d.org) in Python [19]. Because equal variances could not be assumed, the Welch form of the *t* statistic was used without a preliminary variance test. The critical threshold was determined by a random field theory at $\alpha = 0.05$ (two-tailed), controlling the family-wise error rate across the whole series. Suprathreshold clusters indicated significant group differences, and the probability of each cluster is reported.

The discrete variables (Tables 1–3) were analysed using a 2 (group) × 5 (intensity: 20–100% of maximal ball velocity) mixed-design ANOVA. Sphericity was assessed using Mauchly's test, and when it was violated, the degrees of freedom were corrected using the Greenhouse–Geisser method. For all variables, between-group comparisons at each intensity were performed using the Welch form of the independent *t*-test, as equal variances between groups could not be assumed, and Hedges' *g* with 95% confidence intervals was calculated for each comparison. These effect sizes are reported in Tables 1–3, in which statistically significant group differences are highlighted.

As this was a convenience sample, no *a priori* power analysis was performed. A post-hoc sensitivity analysis (G*Power 3.1.9.7) indicated a minimum detectable effect size of Cohen's $d = 1.42$ ($n = 8$ and 10, $\alpha = 0.05$, power = 0.80). Although numerous ANOVAs were conducted across joints and phases, no family-wise correction was applied for the overall number of analyses; the



The mean changes in ball velocity, ball acceleration, and relative ball velocity are presented for the skilled (black solid line) and non-skilled (grey short-dotted line) groups across 20% to 100% of maximum ball velocity. Shaded regions represent the standard deviation. For each group, the vertical solid lines indicate the start (left) and end (right) of the ascending phase of ball acceleration, with black and grey lines representing the skilled and non-skilled groups, respectively. The bold horizontal lines at the bottom of each panel highlight the time intervals in which a statistically significant group difference was identified by one-dimensional statistical parametric mapping (supra-threshold clusters, $\alpha = 0.05$, two-tailed). %max – % of maximum ball velocity

Figure 3. Comparison of ball kinematics between skilled and non-skilled throwers across five throwing intensities

study should therefore be regarded as exploratory. A sensitivity analysis excluding the single left-handed skilled participant ($n = 7$ *vs.* 10) confirmed that all principal outcomes were unchanged. Data were analysed using SPSS (ver. 30.0, IBM SPSS Statistics, Armonk, NY, USA), with significance set at $p < 0.05$.

Results

Absolute and relative ball velocity and ball acceleration

The maximal ball velocity was higher in the skilled group (33.1 ± 1.9 m/s) than in the non-skilled group (24.9 ± 4.0 m/s, $p < 0.001$, $g = 2.44$ [1.27, 3.60]).

Figure 3 illustrates the changes in absolute ball velocity, ball acceleration, and relative ball velocity over the relative time course. SPM was applied to the ball acceleration phase. The absolute ball velocity was higher in the skilled group than in the non-skilled group over the late portion of the throwing motion at every target velocity (20%max: 81–100%, $p = 0.015$; 40%max: 71–100%, $p = 0.005$; 60%max: 83–100%, $p = 0.021$; 80%max: 68–100%, $p = 0.001$; 100%max: 72–100%, $p = 0.006$).

For ball acceleration, the skilled group showed greater positive acceleration than the non-skilled group during the later portion of the motion at 40% (57–64%, $p = 0.006$), 60% (91–98%, $p = 0.016$), and 100% (87–100%, $p = 0.004$) of the maximal ball velocity. No significant difference was detected at 20%, and 80% of the maximal ball velocity. For relative ball velocity, no significant group difference was detected at 20%, 40%, 60%, 80%, or 100% of the maximal ball velocity. At ball release, the relative ball velocities did not differ between the groups (skilled *vs.* non-skilled group: 22.7 ± 1.5 *vs.* 23.1 ± 2.4 [$p = 0.967$]; 41.3 ± 3.1 *vs.* 41.9 ± 2.1 [$p = 0.589$]; 61.7 ± 2.2 *vs.* 63.2 ± 3.5 [$p = 0.526$]; and 81.4 ± 3.0 *vs.* 82.4 ± 5.0 [$p = 0.783$]; % of the maximal ball velocity).

Delta value of absolute and relative ball velocity and phase time

Mauchly's test indicated that the assumption of sphericity was violated for most within-subject effects ($W = 0.000–0.249$, all $p < 0.05$), and the degrees of freedom for these effects were corrected using the Greenhouse–Geisser method ($\varepsilon = 0.250–0.683$). For the remaining effects, sphericity was not violated ($W = 0.325–0.590$, all $p \geq 0.064$) and no correction was ap-

plied. The Mauchly's *W*, *p* values, and Greenhouse–Geisser epsilon for all within-subject effects are provided in Supplementary Table S1.

Table 1 summarises the delta values (maximum minus minimum value) for absolute and relative ball velocity as well as absolute and relative time during the ascending and descending phases of ball acceleration.

A group by intensity interaction was found for the delta values of the absolute ball velocity ($F_{(1.78, 28.50)}$ = 18.41, $p < 0.001$, $\eta^2 = 0.54$, $\varepsilon = 0.45$) and for the relative ball velocity ($F_{(2.13, 34.06)}$ = 6.51, $p = 0.003$, $\eta^2 = 0.51$, $\varepsilon = 0.53$) in the ascending phase of ball acceleration. Post-hoc analysis revealed that in the ascending phase, the delta values for both absolute and relative ball velocities were higher in the skilled group than in the non-skilled group at 40–100% of the maximal ball velocity (Table 1).

A group by intensity interaction was also observed for the relative ball velocity in the descending phase of ball acceleration ($F_{(2.15, 34.33)}$ = 8.73, $p = 0.001$, $\eta^2 = 0.32$, $\varepsilon = 0.54$). In this phase, the delta values for the relative ball velocity were lower in the skilled group than in the non-skilled group at 40%, 60%, 80%, and 100% of the maximal ball velocity (Table 1).

No group by intensity interaction was found for the delta values of the absolute ball velocity in the descending phase ($p = 0.056$), phase time in ascending ($p = 0.626$) or descending ($p = 0.894$) phase, or relative phase time in ascending ($p = 0.473$) and descending ($p = 0.473$) phases of ball acceleration (Table 1).

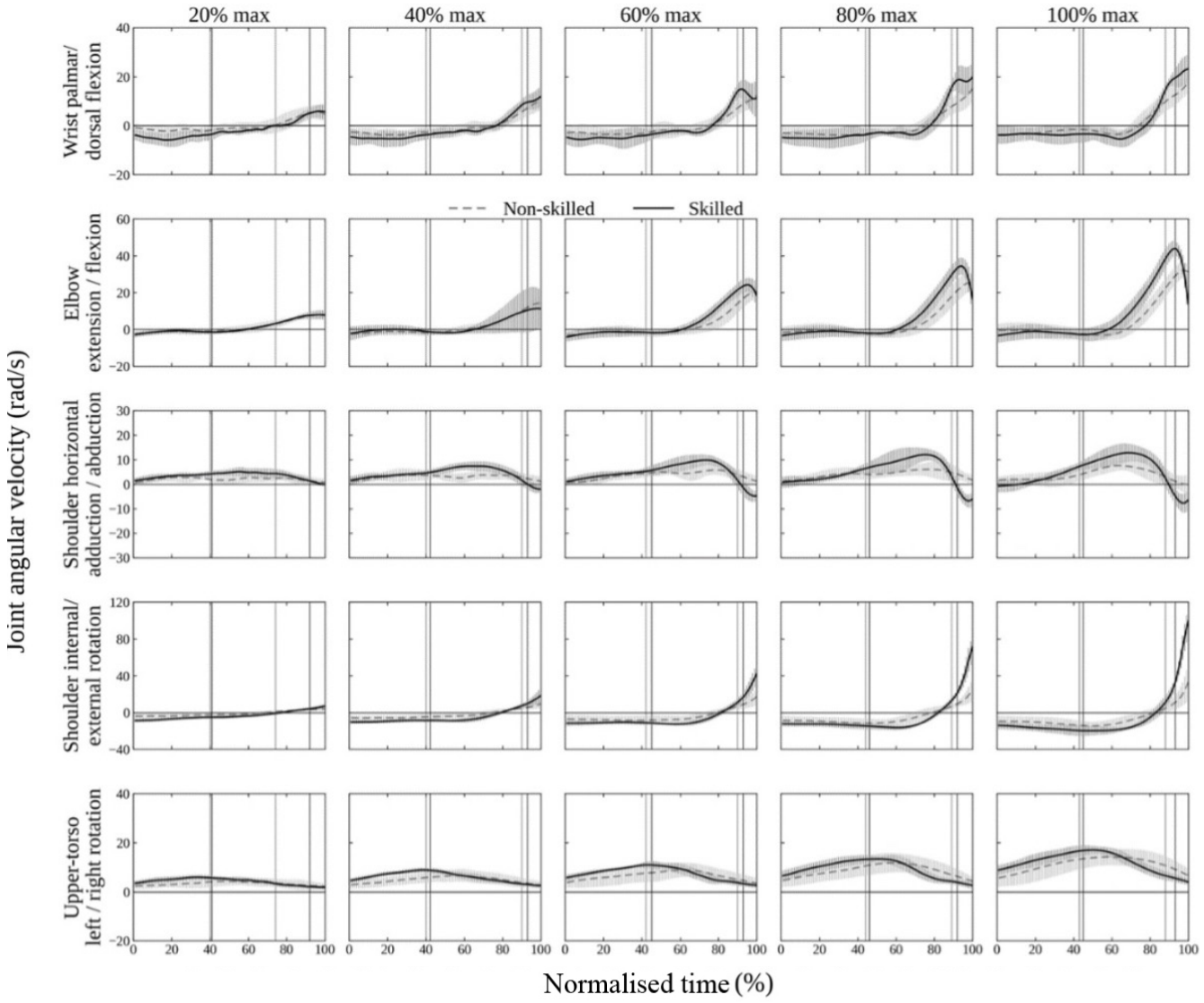
Changes in joint angular velocities

Figure 4 illustrates the changes in joint angular velocities for both groups over the relative time course. In the wrist joint, both groups transitioned from dorsal to palmar flexion around 80% of the relative time across all target ball velocities. In the elbow joint, both groups showed a transition from flexion to extension at approximately 60% of the relative time across all target ball velocities. For shoulder horizontal adduction/abduction, the skilled group tended to augment horizontal abduction near ball release with increasing target ball velocity, whereas the non-skilled group primarily performed horizontal adduction. For shoulder internal/external rotation, both groups transitioned from external to internal rotation at approximately 80% of the relative time. In the upper torso, both groups increased left rotation angular velocity as target ball velocity increased.

Table 1. Ball velocity and temporal phase characteristics for skilled and non-skilled groups across throwing intensities

Variance	Effect	η^2	20%max		40%max		60%max		80%max		100%max	
			skilled	non-skilled	skilled	non-skilled	skilled	non-skilled	skilled	non-skilled	skilled	non-skilled
ΔBall velocity (m/s)												
dscending	G*I	0.54	3.81 ± 1.40	2.73 ± 1.29	**10.10 ± 1.60**	**6.87 ± 1.30**	**15.56 ± 1.63**	**10.32 ± 2.03**	**19.76 ± 1.94**	**13.73 ± 3.36**	**25.89 ± 1.54**	**16.47 ± 4.19**
g [95%*CI*]			0.76 [–0.15, 1.68]		**2.14 [1.03, 3.24]**		**2.68 [1.46, 3.89]**		**2.03 [0.94, 3.12]**		**2.72 [1.49, 3.94]**	
descending	I	0.16	1.86 ± 1.27	1.30 ± 0.90	1.31 ± 0.34	1.47 ± 0.52	2.19 ± 0.40	2.95 ± 0.92	3.84 ± 1.93	4.14 ± 1.54	3.04 ± 0.63	4.93 ± 1.96
g [95%*CI*]			0.49 [–0.40, 1.39]		–0.32 [–1.21, 0.57]		–0.97 [–1.91, –0.04]		–0.16 [–1.05, 0.72]		–1.17 [–2.13, –0.22]	
ΔRelative ball velocity (%)												
ascending	G*I	0.29	11.8 ± 5.0	10.5 ± 5.2	**32.0 ± 4.3**	**27.2 ± 2.7**	**50.0 ± 4.4**	**40.2 ± 4.2**	**63.3 ± 6.6**	**53.1 ± 8.1**	**82.5 ± 2.7**	**64.6 ± 12.0**
g [95%*CI*]			0.24 [–0.65, 1.13]		**1.31 [0.33, 2.28]**		**2.19 [1.07, 3.31]**		**1.30 [0.33, 2.28]**		**1.86 [0.80, 2.92]**	
descending	G*I	0.35	6.3 ± 4.1	5.7 ± 4.1	**3.9 ± 0.9**	**6.1 ± 2.2**	**6.4 ± 2.0**	**13.0 ± 4.4**	**10.2 ± 6.1**	**18.7 ± 7.7**	**4.5 ± 2.4**	**22.1 ± 12.8**
g [95%*CI*]			0.13 [–0.76, 1.01]		**–1.14 [–2.10, –0.19]**		**–1.77 [–2.81, –0.73]**		**–1.16 [–2.12, –0.21]**		**–1.72 [–2.75, –0.68]**	
Phase time (s)												
ascending	I	0.65	0.18 ± 0.06	0.19 ± 0.08	0.16 ± 0.02	0.18 ± 0.05	0.13 ± 0.02	0.13 ± 0.04	0.10 ± 0.02	0.10 ± 0.04	0.09 ± 0.03	0.09 ± 0.04
g [95%*CI*]			–0.18 [–1.07, 0.70]		–0.44 [–1.34, 0.45]		–0.12 [–1.01, 0.76]		–0.10 [–0.98, 0.79]		0.12 [–0.76, 1.01]	
descending	I	0.51	0.08 ± 0.05	0.09 ± 0.08	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.00	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.01 ± 0.00	0.02 ± 0.01
g [95%*CI*]			–0.15 [–1.04, 0.74]		–1.29 [–2.26, –0.31]		–1.54 [–2.55, –0.53]		–0.77 [–1.69, 0.15]		–1.38 [–2.37, –0.40]	
Relative phase time (%)												
ascending	I	0.44	68.4 ± 21.1	68.3 ± 18.1	88.8 ± 4.1	85.0 ± 6.1	89.4 ± 2.3	83.4 ± 7.7	87.0 ± 3.8	81.8 ± 9.4	91.4 ± 3.0	81.2 ± 11.3
g [95%*CI*]			0.01 [–0.88, 0.89]		0.68 [–0.23, 1.59]		0.97 [0.03, 1.90]		0.67 [–0.24, 1.58]		1.11 [0.16, 2.06]	
descending	I	0.44	31.6 ± 21.1	31.7 ± 18.1	11.2 ± 4.1	15.0 ± 6.1	10.6 ± 2.3	16.6 ± 7.7	13.0 ± 3.8	18.2 ± 9.4	8.6 ± 3.0	18.8 ± 11.3
g [95%*CI*]			–0.01 [–0.89, 0.88]		–0.68 [–1.59, 0.23]		–0.97 [–1.90, –0.03]		–0.67 [–1.58, 0.24]		–1.11 [–2.06, –0.16]	

ascending – the ascending phase of ball acceleration, descending – the descending phase of ball acceleration, *g* [95%CI] – Hedges' *g* with 95% confidence intervals is presented beneath each row for the between-group comparison at each intensity
G*I – group by intensity interaction, I – intensity main effect, %max – % of maximum ball velocity
All values are reported as the mean ± standard deviation. Bold values indicate a statistically significant difference between groups ($p < 0.05$). Bold *g* values correspond to statistically significant group differences.



Mean angular velocities for wrist palmar/dorsal flexion, elbow extension/flexion, shoulder horizontal adduction/abduction, shoulder internal/external rotation, and upper torso left/right rotation are compared between the skilled (black solid line) and non-skilled (grey short-dotted line) participants. Shaded regions denote the standard deviation. The vertical solid lines indicate the start (left) and end (right) of the ascending phase of ball acceleration for each group, with black and grey lines representing the skilled and non-skilled groups, respectively.

%max – % of maximum ball velocity

Figure 4. Comparison of joint angular velocities between skilled and non-skilled groups across 20% to 100% of their maximum ball velocity

Maximum and minimum joint angular velocity

Tables 2 and 3 summarise the maximum and minimum joint angular velocities during the ascending and descending phases of ball acceleration, respectively.

Ascending phase of ball acceleration

There was a group by intensity interaction for the maximum angular velocities of the wrist ($F_{(2.32, 37.18)}$ = 7.25, p < 0.001, η^2 = 0.31, ε = 0.58), elbow ($F_{(2.02,32.37)}$ = 28.22, p < 0.001, η^2 = 0.64, ε = 0.51), and shoulder joint (horizontal adduction/abduction: $F_{(2.59, 41.37)}$ = 4.61, p = 0.002, η^2 = 0.22, ε = 0.65, internal/external rotation: $F_{(1.50, 24.02)}$ = 14.27, p < 0.001, η^2 = 0.47, ε = 0.38, Table 2) in the ascending phase of ball acceleration. No significant interaction was found for the upper torso (p = 0.11). Maximum joint angular velocities for the wrist and elbow joints occurred near the end of the ascending phase of ball acceleration in both groups (Figure 4), but the skilled group showed higher angular velocities in both joints than the non-skilled group at 40–100% of the target ball velocity (at 100%max, wrist: g = 2.02 [0.93, 3.10]; elbow: g = 2.99 [1.71, 4.27]; Table 2). For the shoulder joint, maximum angular velocities also occurred at similar relative time points for both groups

(Figure 4), but the skilled group exhibited greater shoulder joint horizontal adduction and internal rotation than the non-skilled group (at 100%max, horizontal adduction: g = 1.56 [0.55, 2.57]; internal rotation: g = 2.25 [1.12, 3.38]; Table 2).

A group main effect was found for the timing of maximum upper torso angular velocity ($F_{(1, 16)}$ = 5.08, p = 0.039, η^2 = 0.24), with the skilled group reaching this point earlier than the non-skilled group (Table 2). No significant interaction was found for the timing of maximum angular velocities in the wrist (p = 0.06), elbow (p = 0.22), or shoulder joints (horizontal adduction/abduction: p = 0.71; internal/external rotation: p = 0.09).

In contrast, there was a group by intensity interaction for the minimum angular velocities for the shoulder horizontal adduction/abduction ($F_{(2.17, 34.76)}$ = 13.69, p < 0.001, η^2 = 0.46, ε = 0.54) and upper torso ($F_{(1.73, 27.70)}$ = 7.66, p < 0.001, η^2 = 0.32, ε = 0.43), and a group main effect for the minimum shoulder internal/external rotation angular velocity ($F_{(1, 16)}$ = 6.48, p = 0.022, η^2 = 0.29). The skilled group showed lower minimum shoulder and upper torso angular velocities than the non-skilled group (Table 2). No significant interaction was found for the other joints (wrist: p = 0.31, elbow: p = 0.52).

A group main effect was found for the timing of minimum joint angular velocity in the shoulder horizontal adduction/abduction ($F_{(1, 16)}$ = 13.93, p = 0.002, η^2 = 0.47) and upper torso ($F_{(1, 16)}$ = 5.70, p = 0.030, η^2 = 0.26). The non-skilled group reached the minimum shoulder horizontal adduction/abduction and upper torso angular velocity earlier than the skilled group (Table 2). The groups differed in the timing of minimum shoulder horizontal adduction/abduction angular velocity at all intensities except 80%max, where the difference did not reach significance (p = 0.058). The timing of minimum angular velocities for the other joints did not differ between the groups (wrist: p = 0.62, elbow: p = 0.82, and shoulder internal/external rotation: p = 0.28).

Descending phase of ball acceleration

A group by intensity interaction was found for the maximum angular velocities of all joints in the descending phase of ball acceleration (wrist: $F_{(2.73, 43.74)}$ = 3.28, p = 0.034, η^2 = 0.17, ε = 0.68, elbow: $F_{(2.47, 39.54)}$ = 8.21, p < 0.001, η^2 = 0.34, ε = 0.62, shoulder horizontal adduction/abduction: $F_{(2.19, 35.08)}$ = 7.90, p < 0.001, η^2 = 0.33, ε = 0.55, shoulder internal/external rotation: $F_{(1.82, 29.12)}$ = 48.05, p < 0.001, η^2 = 0.75, ε = 0.46, upper torso: $F_{(1.93, 30.88)}$ = 11.55, p < 0.001, η^2 = 0.42, ε = 0.48, Table 3). In comparison to the non-skilled group, the skilled group performed faster wrist palmar flexion and elbow extension (Figure 4, Table 3). For shoulder horizontal adduction/abduction velocity, the non-skilled group demonstrated shoulder horizontal adduction across all target ball velocities, while the skilled group showed shoulder horizontal abduction at 40–100% of the target ball velocity (at 100%max, g = –2.02 [–3.11, –0.94]; Figure 4, Table 3). The skilled group also performed faster shoulder internal rotation near ball release (at 100%max, g = 3.49 [2.09, 4.90]) than the non-skilled group across all target ball velocities (Figure 4, Table 3). For the upper torso, the non-skilled group showed faster left rotation (at 100%max, g = –1.81 [–2.86, –0.76]) than the skilled group (Figure 4, Table 3).

The timing of maximum angular velocities in the descending phase of ball acceleration showed a group main effect for the elbow ($F_{(1, 16)}$ = 14.17, p = 0.002, η^2 = 0.47) and shoulder internal/external rotation ($F_{(1, 16)}$ = 9.42, p = 0.007, η^2 = 0.37). The skilled group reached the maximum elbow extension velocity earlier than the non-skilled group (at 100%max, g = –1.46 [–2.45, –0.46]), while the non-skilled group reached the maximum shoulder internal rotation velocity earlier at 20% of target ball velocity (Figure 4, Table 3). The timing of maximum angular velocity did not differ in the wrist (p = 0.35), shoulder horizontal adduction/abduction (p = 0.66), or the upper torso (p = 0.24).

A group by intensity interaction was found for the minimum angular velocity of all joints (wrist: $F_{(2.99, 47.90)}$ = 6.72, p < 0.001, η^2 = 0.30, ε = 0.75, elbow: $F_{(1.66, 26.48)}$ = 6.63, p = 0.007, η^2 = 0.29, ε = 0.41, shoulder horizontal adduction/abduction: $F_{(2.01, 32.18)}$ = 14.38, p < 0.001, η^2 = 0.47, ε = 0.50, shoulder internal/external rotation: $F_{(1.44, 23.02)}$ = 22.13, p < 0.001, η^2 = 0.58, ε = 0.36, upper torso: $F_{(2.31, 37.02)}$ = 4.36, p = 0.004, η^2 = 0.21, ε = 0.58). In the descending phase of ball acceleration, the skilled group showed a lower minimum angular velocity in the elbow, shoulder horizontal adduction/abduction, and upper torso left rotation, but higher minimum angular velocity in the wrist and shoulder internal/external rotation than the non-skilled group (Table 3).

The timing of minimum angular velocities showed a group main effect only for the elbow ($F_{(1, 16)}$ = 8.07, p = 0.012, η^2 = 0.34), with the non-skilled group reaching this point earlier than the skilled group (Table 3). The timing of minimum angular velocities did not differ for the wrist (p = 0.13), shoulder horizontal adduction/abduction (p = 0.14), shoulder internal/external rotation (p = 0.18), or upper torso (p = 0.62).

Table 2. Peak joint angular velocities and their timing during the ascending phase of ball acceleration

Ascending ball acceleration phase		Effect	η^2	Joint angular velocity and appearance instant									
				20%max		20%max		60%max		80%max		100%max	
				skilled	non-skilled	skilled	non-skilled	skilled	non-skilled	skilled	non-skilled	skilled	non-skilled
Wrist palmar (+)/dorsal (–) flexion													
Max	value	G*I	0.31	2.07 ± 3.51	2.38 ± 2.65	**9.70 ± 3.09**	**6.01 ± 3.16**	**15.13 ± 3.73**	7.48 ± 3.63	15.62 ± 5.31	8.88 ± 4.93	19.64 ± 2.39	9.91 ± 5.76
	g [95%*CI*]			–0.09 [–0.98, 0.79]		**1.12 [0.17, 2.08]**		**1.98 [0.90, 3.06]**		**1.26 [0.29, 2.23]**		**2.02 [0.93, 3.10]**	
	timing	I	0.01	79.9% ± 12.7%	75.8% ± 16.6%	92.1% ± 2.4%	85.7% ± 10.9%	92.3% ± 1.6%	86.8% ± 14.3%	91.6% ± 2.3%	88.5% ± 5.9%	93.3% ± 2.6%	89.4% ± 5.8%
	g [95%*CI*]			0.26 [–0.63, 1.15]		0.73 [–0.18, 1.65]		0.48 [–0.42, 1.38]		0.64 [–0.27, 1.54]		0.78 [–0.13, 1.70]	
Min.	value	I	0.18	–4.63 ± 1.28	–2.92 ± 1.60	–4.92 ± 1.43	–4.51 ± 1.55	–4.68 ± 1.04	–4.39 ± 2.34	–5.69 ± 1.93	–4.21 ± 2.06	–6.75 ± 2.38	–4.59 ± 2.57
	g [95%*CI*]			–1.11 [–2.06, –0.16]		–0.26 [–1.15, 0.63]		–0.15 [–1.03, 0.74]		–0.71 [–1.62, 0.20]		–0.83 [–1.75, 0.09]	
	timing	n.s.		49.5% ± 5.6%	45.9% ± 16.6%	51.3% ± 11.1%	55.2% ± 12.2%	55.0% ± 15.6%	55.0% ± 10.9%	63.1% ± 14.1%	55.8% ± 13.4%	64.4% ± 6.8%	62.1% ± 7.6%
	g [95%*CI*]			0.26 [–0.63, 1.15]		–0.32 [–1.21, 0.57]		0.00 [–0.89, 0.89]		0.51 [–0.39, 1.41]		0.30 [–0.59, 1.19]	
Elbow extension (+)/flexion (–)													
Max	value	G*I	0.64	4.41 ± 3.17	4.84 ± 2.80	**14.72 ± 3.88**	**9.99 ± 1.66**	**23.33 ± 4.34**	**13.03 ± 3.59**	**31.88 ± 6.28**	**16.30 ± 5.55**	**44.11 ± 4.28**	**21.74 ± 8.72**
	g [95%*CI*]			–0.14 [–1.03, 0.75]		**1.58 [0.57, 2.59]**		**2.49 [1.32, 3.67]**		**2.52 [1.34, 3.70]**		**2.99 [1.71, 4.27]**	
	timing	I	0.45	80.0% ± 11.1%	79.6% ± 12.4%	92.1% ± 2.3%	90.4% ± 3.4%	93.0% ± 1.4%	90.2% ± 4.3%	92.4% ± 2.2%	89.3% ± 4.9%	92.0% ± 1.5%	89.6% ± 5.9%
	g [95%*CI*]			0.03 [–0.85, 0.92]		0.56 [–0.35, 1.46]		0.80 [–0.12, 1.72]		0.74 [–0.18, 1.65]		0.51 [–0.39, 1.41]	
Min.	value	I	0.21	–1.64 ± 0.79	–1.70 ± 1.26	–2.18 ± 0.88	–2.36 ± 1.29	–2.09 ± 1.20	–2.97 ± 1.37	–2.37 ± 2.05	–3.25 ± 1.82	–2.99 ± 3.63	–4.17 ± 2.98
	g [95%*CI*]			0.05 [–0.84, 0.94]		0.15 [–0.74, 1.04]		0.65 [–0.26, 1.56]		0.44 [–0.46, 1.33]		0.34 [–0.55, 1.23]	
	timing	I	0.21	44.6% ± 4.4%	42.5% ± 13.8%	46.6% ± 5.2%	48.3% ± 9.5%	51.1% ± 4.1%	51.1% ± 12.5%	50.8% ± 3.2%	51.8% ± 10.2%	48.6% ± 4.2%	51.7% ± 9.8%
	g [95%*CI*]			0.19 [–0.70, 1.08]		–0.20 [–1.09, 0.69]		0.00 [–0.88, 0.89]		–0.13 [–1.01, 0.76]		–0.37 [–1.27, 0.52]	
Shoulder horizontal adduction (+)/abduction (–)													
Max	value	G*I	0.22	**5.54 ± 1.76**	**3.77 ± 1.34**	**7.88 ± 1.52**	**5.68 ± 1.33**	**10.18 ± 2.45**	**7.08 ± 1.20**	**12.91 ± 2.66**	**7.34 ± 2.59**	**13.67 ± 3.41**	8.91 ± 2.44
	g [95%*CI*]			**1.10 [0.15, 2.04]**		**1.48 [0.48, 2.48]**		**1.59 [0.58, 2.61]**		**2.02 [0.94, 3.11]**		**1.56 [0.55, 2.57]**	
	timing	I	0.24	56.6% ± 7.3%	57.0% ± 23.9%	65.6% ± 5.5%	63.3% ± 19.2%	72.4% ± 5.2%	70.8% ± 12.7%	73.4% ± 7.0%	69.2% ± 15.8%	68.0% ± 5.9%	67.8% ± 9.0%
	g [95%*CI*]			–0.02 [–0.90, 0.87]		0.15 [–0.74, 1.04]		0.15 [–0.74, 1.03]		0.31 [–0.58, 1.20]		0.02 [–0.86, 0.91]	
Min.	value	G*I	0.46	**2.40 ± 1.74**	**0.81 ± 1.24**	0.41 ± 2.87	1.29 ± 1.65	**–0.87 ± 3.63**	**2.34 ± 2.39**	**–0.60 ± 3.26**	**3.05 ± 2.02**	**–4.68 ± 3.29**	**1.97 ± 2.73**
	g [95%*CI*]			**1.02 [0.08, 1.96]**		–0.37 [–1.26, 0.52]		**–1.02 [–1.96, –0.08]**		**–1.31 [–2.29, –0.34]**		**–2.12 [–3.22, –1.02]**	
	timing	G, I	0.31 0.47	**73.5% ± 21.6%**	**52.4% ± 16.9%**	**92.3% ± 2.4%**	**71.8% ± 18.4%**	**93.5% ± 1.1%**	**78.1% ± 17.7%**	86.6% ± 18.1%	67.9% ± 20.7%	**93.4% ± 2.4%**	**77.0% ± 22.2%**
	g [95%*CI*]			**1.05 [0.11, 2.00]**		**1.40 [0.42, 2.39]**		**1.10 [0.15, 2.05]**		0.91 [–0.02, 1.84]		**0.93 [0.00, 1.86]**	
Shoulder internal (+)/external (–) rotation													
Max	value	G*I	0.47	1.68 ± 3.65	2.11 ± 1.92	**9.85 ± 4.61**	**4.66 ± 1.91**	**16.45 ± 6.35**	**5.87 ± 3.56**	**18.29 ± 6.87**	**7.09 ± 4.18**	**34.58 ± 17.12**	**5.35 ± 6.58**
	g [95%*CI*]			–0.15 [–1.03, 0.74]		**1.47 [0.47, 2.46]**		**2.02 [0.94, 3.11]**		**1.93 [0.86, 3.00]**		**2.25 [1.12, 3.38]**	
	timing	I	0.46	80.9% ± 12.0%	75.5% ± 16.3%	92.3% ± 2.4%	88.8% ± 4.9%	93.5% ± 1.1%	90.2% ± 4.3%	92.4% ± 2.2%	89.3% ± 4.9%	93.5% ± 2.6%	89.6% ± 5.9%
	g [95%*CI*]			0.35 [–0.54, 1.24]		0.83 [–0.10, 1.75]		0.95 [0.02, 1.89]		0.74 [–0.18, 1.65]		0.79 [–0.13, 1.71]	
Min.	value	I, G	0.89 0.29	**–5.52 ± 1.01**	**–3.13 ± 2.69**	**–9.72 ± 1.40**	**–5.78 ± 2.77**	–13.40 ± 1.59	–10.20 ± 4.59	–17.07 ± 2.48	–12.95 ± 5.37	–21.19 ± 4.43	–16.12 ± 5.26
	g [95%*CI*]			**–1.07 [–2.02, –0.13]**		**–1.65 [–2.68, –0.63]**		–0.85 [–1.77, 0.08]		–0.90 [–1.83, 0.03]		**–0.98 [–1.92, –0.04]**	
	timing	I	0.25	44.3% ± 5.1%	45.0% ± 14.8%	54.1% ± 7.1%	48.0% ± 12.3%	57.6% ± 7.2%	50.6% ± 12.2%	57.3% ± 7.4%	48.6% ± 9.3%	49.1% ± 6.8%	49.8% ± 8.7%
	g [95%*CI*]			–0.06 [–0.95, 0.82]		0.56 [–0.34, 1.47]		0.65 [–0.26, 1.56]		0.97 [0.03, 1.90]		–0.08 [–0.97, 0.80]	
Upper torso left (+)/right (–) rotation													
Max	value	I	0.93	5.93 ± 0.92	4.79 ± 1.91	8.94 ± 1.09	7.34 ± 2.47	10.94 ± 1.80	9.76 ± 2.89	14.54 ± 1.10	12.33 ± 3.72	17.63 ± 1.69	14.97 ± 3.61
	g [95%*CI*]			0.70 [–0.21, 1.61]		0.77 [–0.15, 1.68]		0.46 [–0.44, 1.35]		0.73 [–0.19, 1.64]		0.86 [–0.06, 1.79]	
	timing	G	0.24	49.4% ± 8.6%	51.2% ± 15.8%	**46.4% ± 7.8%**	**54.4% ± 7.6%**	**49.9% ± 2.9%**	**58.7% ± 9.5%**	53.5% ± 6.1%	56.7% ± 8.0%	52.8% ± 6.9%	58.2% ± 14.7%
	g [95%*CI*]			–0.13 [–1.02, 0.75]		**–0.99 [–1.93, –0.06]**		**–1.14 [–2.09, –0.19]**		–0.42 [–1.32, 0.47]		–0.44 [–1.33, 0.46]	
Min.	value	G*I	0.32	3.07 ± 1.55	2.86 ± 1.39	3.00 ± 0.61	3.68 ± 1.89	3.15 ± 1.19	5.18 ± 3.17	**3.86 ± 0.82**	**7.24 ± 3.75**	**5.40 ± 1.70**	**9.84 ± 4.19**
	g [95%*CI*]			0.14 [–0.74, 1.03]		–0.44 [–1.33, 0.46]		–0.77 [–1.69, 0.15]		**–1.12 [–2.08, –0.17]**		**–1.27 [–2.24, –0.30]**	
	timing	I, G	0.16 0.26	77.1% ± 14.2%	67.6% ± 21.3%	92.3% ± 2.4%	85.2% ± 12.8%	89.8% ± 7.3%	79.6% ± 20.8%	90.3% ± 5.2%	77.3% ± 22.7%	**93.5% ± 2.6%**	**70.5% ± 28.7%**
	g [95%*CI*]			0.49 [–0.41, 1.39]		0.69 [–0.22, 1.60]		0.59 [–0.31, 1.50]		0.71 [–0.20, 1.62]		**1.02 [0.08, 1.96]**	

G*I – group by intensity interaction, I – intensity main effect, G – group main effect, n.s. – not significant, %max – % of maximum ball velocity, *g* [95%*CI*] – Hedges' g with 95% confidence intervals is presented beneath each row for the between-group comparison at each intensity.
Bold g values correspond to statistically significant group differences.
All values are presented as the mean ± standard deviation. Max and Min. indicate the maximum (Max) and minimum (Min.) joint angular velocity (rad/s) and the relative time (%) at which this peak value occurred.
Bold values indicate a statistically significant group difference ($p < 0.05$). The Effect column indicates the significant effect(s) in the two-way mixed ANOVA (group×intensity), and the η^2 column shows the effect size for each.

Table 3. Peak joint angular velocities and their timing during the descending phase of ball acceleration

Descending ball acceleration phase		Effect	η^2	Joint angular velocity and appearance instant									
				20%max		40%max		60%max		80%max		100%max	
				skilled	non-skilled	skilled	non-skilled	skilled	non-skilled	skilled	non-skilled	skilled	non-skilled
Wrist palmar (+)/dorsal (–) flexion													
Max	value	G*I	0.17	6.28 ± 2.68	6.93 ± 3.36	12.50 ± 3.60	10.43 ± 4.11	15.74 ± 5.09	12.61 ± 4.09	**22.37 ± 5.86**	**15.00 ± 4.72**	**24.16 ± 5.74**	**18.99 ± 3.70**
	g [95%*CI*]			–0.20 [–1.09, 0.69]		0.51 [–0.39, 1.41]		0.65 [–0.25, 1.56]		**1.34 [0.36, 2.31]**		**1.05 [0.10, 1.99]**	
	timing	n.s.		96.3% ± 3.7%	95.2% ± 5.4%	97.8% ± 3.6%	99.4% ± 1.1%	96.4% ± 3.1%	98.9% ± 3.5%	96.5% ± 3.3%	98.8% ± 3.8%	97.6% ± 3.1%	97.3% ± 5.0%
	g [95%*CI*]			0.21 [–0.68, 1.10]		–0.62 [–1.53, 0.28]		–0.72 [–1.64, 0.19]		–0.61 [–1.52, 0.29]		0.07 [–0.81, 0.96]	
Min.	value	G*I	0.30	2.15 ± 3.79	2.21 ± 2.60	9.25 ± 3.57	6.34 ± 4.07	9.69 ± 6.39	7.85 ± 3.77	**15.29 ± 4.76**	**9.46 ± 5.36**	**20.05 ± 4.41**	**10.34 ± 4.41**
	g [95%*CI*]			–0.02 [–0.90, 0.87]		0.61 [–0.29, 1.52]		0.36 [–0.53, 1.25]		**1.09 [0.14, 2.04]**		**2.10 [1.00, 3.20]**	
	timing	I	0.39	83.6% ± 12.2%	84.2% ± 13.8%	95.6% ± 2.1%	91.5% ± 3.5%	98.0% ± 2.6%	92.3% ± 5.0%	94.9% ± 3.4%	92.1% ± 3.7%	96.5% ± 3.3%	93.6% ± 5.4%
	g [95%*CI*]			–0.04 [–0.93, 0.84]		1.34 [0.36, 2.31]		1.32 [0.34, 2.29]		0.75 [–0.17, 1.66]		0.60 [–0.30, 1.51]	
Elbow extension (+)/flexion (–)													
Max	value	G*I	0.34	8.18 ± 2.41	8.46 ± 1.55	16.19 ± 3.82	14.46 ± 3.00	**24.91 ± 3.83**	20.76 ± 4.06	**34.77 ± 4.92**	**26.19 ± 4.47**	**39.76 ± 7.74**	**33.12 ± 3.95**
	g [95%*CI*]			–0.14 [–1.02, 0.75]		0.49 [–0.41, 1.39]		**1.00 [0.06, 1.93]**		**1.75 [0.71, 2.79]**		**1.07 [0.12, 2.01]**	
	timing	G	0.47	96.4% ± 3.6%	94.8% ± 7.0%	**96.8% ± 2.3%**	**99.3% ± 1.1%**	**96.6% ± 1.6%**	**98.7% ± 1.5%**	**94.5% ± 1.1%**	**98.4% ± 1.8%**	**95.1% ± 2.0%**	**98.2% ± 2.0%**
	g [95%*CI*]			0.26 [–0.63, 1.15]		**–1.41 [–2.40, –0.42]**		**–1.28 [–2.25, –0.31]**		**–2.46 [–3.63, –1.29]**		**–1.46 [–2.45, –0.46]**	
Min.	value	G*I	0.29	4.50 ± 3.21	4.43 ± 2.52	13.08 ± 3.03	10.87 ± 1.76	17.65 ± 6.30	14.81 ± 3.68	16.58 10.14	18.96 ± 5.74	**13.80 ± 10.22**	**24.58 ± 8.59**
	g [95%*CI*]			0.03 [–0.86, 0.91]		0.88 [–0.05, 1.80]		0.54 [–0.36, 1.44]		–0.28 [–1.17, 0.61]		**–1.10 [–2.05, –0.15]**	
	timing	I, G	0.36 0.34	82.9% ± 13.2%	84.4% ± 15.1%	**96.9% ± 4.5%**	**91.4% ± 3.4%**	**98.4% ± 3.0%**	**91.2% ± 4.3%**	**98.3% ± 3.3%**	**91.0% ± 5.8%**	**100.0% ± 0.0%**	**91.3% ± 6.9%**
	g [95%*CI*]			–0.10 [–0.99, 0.78]		**1.33 [0.35, 2.31]**		**1.80 [0.76, 2.85]**		**1.43 [0.44, 2.42]**		**1.60 [0.59, 2.62]**	
Shoulder horizontal adduction (+)/abduction (–)													
Max	value	G*I	0.33	2.94 ± 2.53	2.46 ± 1.55	**–0.06 ± 2.69**	**2.70 ± 1.65**	**–1.88 ± 3.14**	**3.59 ± 1.99**	**–2.11 ± 5.39**	**4.02 ± 2.17**	**–5.57 ± 3.79**	**2.20 ± 3.56**
	g [95%*CI*]			0.22 [–0.67, 1.11]		**–1.21 [–2.18, –0.25]**		**–2.04 [–3.13, –0.95]**		**–1.49 [–2.49, –0.49]**		**–2.02 [–3.11, –0.94]**	
	timing	I	0.41	83.0% ± 10.1%	85.0% ± 12.5%	93.3% ± 2.4%	92.1% ± 3.3%	95.6% ± 2.8%	91.9% ± 5.1%	94.6% ± 3.9%	94.8% ± 6.2%	96.0% ± 3.9%	94.4% ± 6.6%
	g [95%*CI*]			–0.17 [–1.05, 0.72]		0.37 [–0.52, 1.27]		0.83 [–0.09, 1.75]		–0.03 [–0.92, 0.85]		0.27 [–0.62, 1.16]	
Min.	value	G*I	0.47	–0.06 ± 0.86	0.25 ± 1.29	**–2.15 ± 1.50**	**1.13 ± 1.75**	**–5.37 ± 2.35**	**1.10 ± 2.00**	**–7.11 ± 2.74**	**1.21 ± 2.38**	**–8.07 ± 3.47**	**–1.04 ± 3.01**
	g [95%*CI*]			–0.26 [–1.15, 0.63]		**–1.90 [–2.96, –0.83]**		**–2.86 [–4.11, –1.60]**		**–3.12 [–4.43, –1.80]**		**–2.08 [–3.18, –0.98]**	
	timing	n.s.		100.0% ± 0.0%	95.0% ± 8.8%	99.3% ± 1.2%	98.8% ± 2.1%	99.0% ± 1.5%	99.1% ± 2.2%	97.6% ± 1.6%	96.1% ± 4.8%	97.9% ± 2.0%	96.1% ± 5.2%
	g [95%*CI*]			0.73 [–0.19, 1.64]		0.24 [–0.64, 1.13]		–0.05 [–0.93, 0.84]		0.39 [–0.50, 1.28]		0.41 [–0.48, 1.30]	
Shoulder internal (+)/external (–) rotation													
Max	value	G*I	0.75	6.88 ± 2.07	3.97 ± 2.29	**18.52 ± 8.19**	**9.47 ± 4.42**	**42.16 ± 10.98**	**17.40 ± 9.81**	**71.53 ± 12.85**	**25.17 ± 12.91**	**99.48 ± 14.76**	**33.20 ± 20.28**
	g [95%*CI*]			**1.27 [0.30, 2.23]**		**1.36 [0.38, 2.34]**		**2.28 [1.15, 3.41]**		**3.43 [2.04, 4.81]**		**3.49 [2.09, 4.90]**	
	timing	G	0.37	**100.0% ± 0.0%**	**95.9% ± 3.8%**	100.0% ± 0.0%	100.0% ± 0.0%	100.0% ± 0.0%	100.0% ± 0.0%	100.0% ± 0.0%	100.0% ± 0.0%	100.0% ± 0.0%	100.0% ± 0.0%
	g [95%*CI*]			**1.39 [0.40, 2.37]**		n.s.		n.s.		n.s.		n.s.	
Min.	value	G*I	0.58	1.91 ± 3.71	1.99 ± 1.98	**11.12 ± 5.41**	**4.93 ± 2.01**	**20.58 ± 8.01**	**7.13 ± 4.02**	**25.09 ± 7.96**	**9.26 ± 5.63**	**53.56 ± 21.64**	**8.99 ± 8.61**
	g [95%*CI*]			–0.03 [–0.91, 0.86]		**1.52 [0.52, 2.52]**		**2.10 [1.00, 3.20]**		**2.23 [1.11, 3.36]**		**2.70 [1.48, 3.92]**	
	timing	I	0.40	81.9% ± 12.0%	81.6% ± 13.6%	93.3% ± 2.4%	91.6% ± 3.6%	94.5% ± 1.1%	91.2% ± 4.3%	93.4% ± 2.2%	91.0% ± 3.9%	94.5% ± 2.6%	90.1% ± 5.5%
	g [95%*CI*]			0.02 [–0.87, 0.91]		0.50 [–0.40, 1.40]		0.95 [0.02, 1.89]		0.69 [–0.22, 1.60]		0.93 [–0.00, 1.86]	
Upper torso left (+)/right (–) rotation													
Max	value	G*I	0.42	3.13 ± 1.51	3.30 ± 2.12	2.91 ± 0.65	3.79 ± 2.09	3.26 ± 1.09	5.19 ± 2.90	**3.79 ± 0.81**	**7.08 ± 2.99**	**4.95 ± 1.61**	**10.15 ± 3.36**
	g [95%*CI*]			–0.08 [–0.97, 0.80]		–0.52 [–1.42, 0.38]		–0.80 [–1.72, 0.12]		**–1.36 [–2.34, –0.38]**		**–1.81 [–2.86, –0.76]**	
	timing	I	0.40	82.3% ± 12.4%	84.1% ± 10.8%	93.8% ± 1.7%	92.0% ± 4.3%	95.3% ± 2.2%	91.8% ± 5.1%	94.1% ± 2.2%	90.8% ± 5.7%	94.6% ± 2.6%	90.1% ± 5.5%
	g [95%*CI*]			–0.15 [–1.04, 0.73]		0.49 [–0.41, 1.39]		0.81 [–0.11, 1.73]		0.71 [–0.21, 1.62]		0.96 [0.02, 1.89]	
Min.	value	G*I	0.21	1.83 ± 0.48	2.11 ± 1.23	2.48 ± 0.69	2.76 ± 1.44	2.57 ± 0.82	3.43 ± 2.19	2.64 ± 1.41	4.27 ± 2.05	**3.96 ± 1.29**	**6.69 ± 2.91**
	g [95%*CI*]			–0.27 [–1.16, 0.62]		–0.23 [–1.12, 0.66]		–0.47 [–1.37, 0.43]		–0.86 [–1.79, 0.06]		**–1.11 [–2.06, –0.16]**	
	timing	n.s.		98.4% ± 2.8%	98.0% ± 4.4%	99.8% ± 0.7%	99.5% ± 1.6%	99.5% ± 1.4%	99.4% ± 1.9%	99.9% ± 0.4%	99.4% ± 1.9%	100.0% ± 0.0%	99.9% ± 0.3%
	g [95%*CI*]			0.09 [–0.79, 0.98]		0.19 [–0.70, 1.07]		0.06 [–0.83, 0.94]		0.31 [–0.58, 1.20]		0.40 [–0.49, 1.30]	

G*I – group by intensity interaction, I – intensity main effect, G – group main effect, n.s. – not significant, %max – % of maximum ball velocity, *g* [95%*CI*] – Hedges' g with 95% confidence intervals is presented beneath each row for the between–group comparison at each intensity
All values are presented as the mean ± standard deviation. Max and Min. indicate the maximum (Max) and minimum (Min.) joint angular velocity (rad/s) and the relative time (%) at which this peak value occurred.
Bold values indicate a statistically significant group difference ($p < 0.05$). The Effect column indicates the significant effect(s) in the two–way mixed ANOVA (group×intensity), and the η^2 column shows the effect size for each. Bold *g* values correspond to statistically significant group differences.

Discussion

This study aimed to clarify the fundamental differences in movement strategies for regulating ball velocity between skilled and non-skilled groups under matched relative effort conditions. We addressed this aim by comparing groups with distinct maximal ball velocities (the skilled group: 33.1 ± 1.9 m/s *vs.* the non-skilled group: 24.9 ± 4.0 m/s) and evaluating their performance at identical relative intensities (20–80% of the maximal ball velocity). The successful matching of ball velocity at release between groups (Figure 3) provides a sound basis for our kinematic comparisons. In addition, the skilled group was approximately three years younger than the non-skilled group. Because participants in both groups were young adults – an age range in which the growth and maturation of gross motor performance are essentially complete [20] – this age difference is unlikely to account for the observed differences in throwing skill. Indeed, the skilled group threw faster despite being younger, which argues against age or maturation acting as a simple confounder. For this reason, age was not included as a covariate in the analyses.

Throwing movement time and ball acceleration

Ball acceleration near ball release tended to be greater in the skilled group, which is consistent with their higher absolute ball velocity (Figure 3). However, despite these group differences in the absolute ball velocity and acceleration, we found no significant group difference in the absolute or relative time of the overall throwing motion, nor in the duration of the ascending and descending phases of ball acceleration (Table 1). These results suggest that, regardless of throwing skill level, throwers employ a common strategy of shortening the total movement time to increase ball velocity, without altering the relative proportion of the acceleration phase.

While the overall timing was similar, the way in which ball velocity was generated differed substantially between the groups. Excluding the 20% of maximal ball velocity condition, both groups primarily increased ball velocity during the ascending phase of ball acceleration (Table 1). However, the skilled group generated ~ 80% of their target ball velocity during the ascending phase of ball acceleration, whereas the non-skilled group achieved only ~ 65% (Table 1). Consequently, to reach a target ball velocity, the non-skilled group had to generate a greater proportion of ball velocity during the descending phase of ball acceleration. These findings highlight a fundamental difference in how skilled and non-skilled throwers distribute their ball velocity throughout the ball acceleration phase, suggesting that the underlying joint angular velocity strategies may also differ.

Joint angular velocity strategies in the ascending phase of ball acceleration

During the ascending phase of ball acceleration, both groups increased the magnitude of angular velocities by increasing maximum values and decreasing minimum values for the wrist, elbow, and shoulder joint angular velocities (Table 2). The skilled group exhibited a greater maximum and a similar minimum angular velocity for wrist palmar flexion and elbow extension in comparison to the non-skilled group, with no difference in timing (Figure 4, Table 2). This suggests that the skilled group simply moved their upper arm segments faster than the non-skilled group. For the shoulder, the skilled group showed greater maximum values for horizontal adduction and internal rotation at similar timings, and larger-magnitude minimum values for horizontal abduction at later timings in comparison to the non-skilled group (Table 2). These results indicate that the skilled group amplified the magnitude of their shoulder joint angular velocities not only by increasing the maximum value but also by decreasing the minimum value and shifting its time. The skilled group also exhibited a similar movement strategy in the upper torso. In a previous study on handball throwing [21], the throwing time (defined as the interval from maximal pelvis rotation velocity to ball release) did not differ according to the thrower's performance level. Collectively, these findings suggest that skilled throwers use a distinct movement strategy, as described by Wagner *et al.* [22], to amplify the magnitude of joint angular velocities in the wrist, elbow, shoulder, and upper torso during the ascending phase of ball acceleration.

Joint angular velocity strategies in the descending phase of ball acceleration

In the descending phase of ball acceleration, both groups increased the magnitude of maximum and minimum angular velocities in wrist palmar flexion, shoulder internal rotation, and upper torso left rotation as target ball velocity increased (Table 3). However, both maximum and minimum values were higher in the skilled group for wrist palmar flexion and shoulder internal rotation, but lower for upper torso left rotation in comparison to the non-skilled group. These

results imply that the skilled group may increase the transfer of interaction torque from the upper torso to the upper arm by attenuating the upper torso left rotation at ball release [23, 24]. Furthermore, the skilled group exhibited shoulder horizontal abduction, whereas the non-skilled group primarily showed horizontal adduction, with the difference becoming more pronounced at higher target ball velocities (Figure 4, Table 3). This distinction in movement direction and amplitude in shoulder horizontal adduction/abduction between the groups could be a key factor in the skilled group's ability to generate greater shoulder internal rotation velocity, a finding consistent with Ishida *et al.* [25], who reported higher shoulder abduction and internal rotation velocity, as well as later peak angular velocities, in senior pitchers than in junior pitchers. In addition, for the elbow, the skilled group's maximum extension velocity occurred prior to the minimum value, whereas in the non-skilled group it occurred after the minimum value (Table 3). This suggests that the skilled group actively attenuated elbow extension before ball release. This earlier attainment of maximum elbow extension velocity may be a strategy used to increase shoulder horizontal abduction velocity, as reported by Feltner and Nelson [26] and Hore *et al.* [27].

Taken together, these findings indicate that in the descending phase of ball acceleration, the skilled throwers use a sophisticated strategy involving attenuating upper torso left rotation and achieving maximum elbow extension velocity early to induce shoulder horizontal abduction, which may augment shoulder internal rotation. Conversely, the non-skilled group employed a movement strategy that did not abruptly inhibit shoulder horizontal adduction, and thus did not inhibit elbow extension.

Recommendations and future directions

Our findings revealed that while both the skilled and non-skilled groups share a common strategy for motion timing, the amplitude and timing of joint angular velocities, particularly those of the shoulder, differ significantly. We observed that a difference in shoulder joint angular velocity was already present at the lowest intensity (*i.e.*, 20% of maximal ball velocity), suggesting that the skill-level difference is inherent to the fundamental movement pattern rather than merely a high-effort strategy.

These results suggest several practical implications for ball-throwing skill development. Although targeted training can improve throwing velocity in throwing athletes [28], our findings suggest that the coordination pattern itself, rather than throwing effort alone, should also be a focus of instruction. We suggest that non-skilled throwers may benefit from training aimed at activating the latissimus dorsi, as this muscle is a key contributor to both shoulder horizontal abduction and internal rotation [29]. In a previous study comparing latissimus dorsi activity during the pitching motion between university and amateur pitchers, the university pitchers exhibited significantly greater activity during the acceleration phase [30]. Developing this activation may help non-skilled throwers achieve the shoulder horizontal abduction observed in skilled throwers. Subsequently, they could then practise extending the elbow prior to ball release to increase shoulder horizontal abduction and internal rotation, as shown by Feltner and Dapena [6], Feltner [7], and Ishida *et al.* [25]. Building on these movement-specific recommendations, our data further suggest that pitching exercises at intensities of ≥ 40% of the maximal ball velocity may be particularly effective for skill acquisition, as the number of joints showing angular velocity differences between the skilled and non-skilled groups increased at these higher intensities. We advance this as a hypothesis to be tested in future intervention studies rather than as an established prescription.

Future studies should investigate muscle activation patterns, particularly of the latissimus dorsi and other key shoulder rotators, to further clarify the neuromuscular mechanisms underlying the differences in movement strategy observed here. Additionally, a longitudinal study tracking the development of these strategies in novice throwers could provide valuable insights into the learning process.

Limitations

Several limitations should be acknowledged. First, the sample size was small (eight skilled and ten non-skilled participants). The post-hoc sensitivity analysis reported in the Methods indicated that only large effects (Cohen's $d \geq 1.42$) could be detected at 80% power; hence, smaller but potentially meaningful between-group differences may have gone undetected. The non-significant comparisons should therefore be interpreted with caution. The small and specific sample also limits the extent to which the findings generalise to other populations. Second, for each participant, the five intensity conditions were presented in the same fixed order, from the highest to the lowest target velocity (a descending block order), rather than in a randomised order. This design was chosen to reduce participant burden and to help participants cali-

brate the lower intensities relative to their maximal effort. Consequently, systematic order or fatigue effects cannot be ruled out. This is of particular concern for the lower-intensity conditions, which were always performed last and may therefore have been more affected by accumulated fatigue. Third, two successful trials were obtained *per* condition, and a single representative trial was analysed for each participant rather than an average of the two, because averaging can generate an intermediate value that does not correspond to any movement actually performed [31]. This choice, together with the limited number of trials, means that within-participant movement variability could not be quantified directly. We did not summarise reliability using an intraclass correlation coefficient. Such an index is governed by the ratio of between-participant to trial-to-trial variance, and trial-to-trial variability is itself expected to differ between skill levels [32]' thus, a lower value in the non-skilled group would reflect that difference rather than lower measurement precision. Future work with more trials *per* condition is needed to quantify movement variability directly. Fourth, the study was cross-sectional and therefore cannot directly address how the skilled strategy develops over time. Longitudinal work would be required to characterise this developmental trajectory. Finally, only upper-body kinematics were measured. This constrains our interpretation in two respects. Because joint kinetics were not computed, our statements regarding interaction torque and muscle activity are inferential rather than based on direct measurement and should be regarded as hypotheses to be tested in future kinetic and electromyographic studies. In addition, muscle volume and strength – which have been positively associated with throwing velocity in previous training studies [28] – were not assessed; therefore, we cannot determine the extent to which the group differences reflect neuromuscular capacity as opposed to movement coordination.

Conclusions

This study examined fundamental differences in movement strategies for regulating ball velocity between skilled and non-skilled throwers performing at matched relative effort levels. While both groups shared a common strategy for overall motion timing, their approaches to generating ball velocity were distinct. The skilled group amplified the magnitude of their joint angular velocities at the wrist, elbow, and shoulder during the ascending phase of ball acceleration, whereas the non-skilled group relied more heavily on the descending phase to generate a substantial portion of their ball velocity. These findings indicate that the way in which ball velocity is regulated differs with skill level: rather than simply varying the overall effort, skilled throwers modulated the magnitude and timing of their joint angular velocities to achieve the required ball velocity.

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Ethical approval

The research related to human use complied with all the relevant national regulations and institutional policies, followed the tenets of the Declaration of Helsinki, and was approved by the Ethics Committee at the Graduate School of Osaka University of Health and Sport Sciences (approval No.: 10-17).

Informed consent

Informed consent has been obtained from all individuals included in this study.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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