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Over-powering in target-aimed throwing: Effects of target distance and task-goal instruction on movement smoothness and coordination

Tsubasa Wakatsuki

twakatsuki@go.tuat.ac.jp

Tokyo University of Agriculture and Technology

Kohei Kawata

Tokyo University of Agriculture and Technology

Hideyuki Tanaka

Tokyo University of Agriculture and Technology

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Title:

Over-powering in target-aimed throwing: Effects of target distance and task-goal instruction on movement smoothness and coordination

Authors:

Tsubasa Wakastuki[1*], Kohei Kawata[2], Hideyuki Tanaka[1*]

Affiliations:

[1]Laboratory of Human Movement Science, Institute of Engineering, Tokyo University of Agriculture and Technology

2-24-16 Nakacho, Koganei, Tokyo, 184-8588, Japan

[2]Major in Mechanical Systems Engineering, Graduate School of Engineering, Tokyo University of Agriculture and Technology

2-24-16 Nakacho, Koganei, Tokyo, 184-8588, Japan

Corresponding Author:

Tsubasa Wakastuki

e-mail: twakatsuki@go.tuat.ac.jp

ORCID ID: 0000-0002-8496-5998

Hideyuki Tanaka

e-mail: tanahide@cc.tuat.ac.jp

ORCID ID: 0000-0001-5988-8807

Abstract

Over-powering, that is, producing movement output that exceeds biomechanical task requirements, may impair motor performance; however, the conditions under which it arises and its specific costs remain underexplored. This study introduced a physics-based

reachability framework to dissociate biomechanically required from superfluous velocity increases and examined how over-powering affects movement smoothness and inter-joint coordination in a target-aimed throwing task. Thirteen participants threw a tennis ball toward a fixed-size target under two task-goal instructions (velocity-focused and accuracy-focused) and from two distances (3.0 m and 4.5 m). Release parameters, inter-joint coordination assessed via principal component analysis, and movement smoothness quantified by jerk costs were analyzed. Increasing the target distance led to coordinated adjustments across all release parameters, whereas the velocity-focused instruction selectively increased the release velocity without significantly altering the release angle or height. The reachability analysis revealed that velocity increases under accuracy-focused conditions were biomechanically necessary, whereas those under velocity-focused conditions were consistent with superfluous production, that is, over-powering. These superfluous velocity increases were associated with reduced movement smoothness and weakened inter-joint coordination without improving throwing accuracy. This study provides novel experimental evidence that over-powering is dissociable from biomechanically required velocity increases and carries measurable motor control costs, consistent with predictions from minimum jerk theory and optimal feedback control theory. Jerk cost may serve as a practical behavioral marker of over-powering in goal-directed throwing tasks.

Keywords: reachability analysis; movement smoothness; inter-joint coordination; task-goal instruction; jerk cost; speed-accuracy tradeoff

Statements and Declarations

Competing Interests

The authors declare that they have no competing interests.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Ethical Consideration and Informed Consent

This study was approved by the Research Ethics Review Board of Tokyo University of Agriculture and Technology, and all procedures were conducted in accordance with the relevant guidelines and regulations. Written informed consent was obtained from all participants prior to participation.

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1. Introduction

In target-aimed throwing, individuals sometimes generate segment velocities (i.e., limb movement velocities) that exceed biomechanical task requirements, a phenomenon operationally defined as *over-powering*. This concept may resemble what is colloquially described as "trying too hard," but here it is defined in strictly biomechanical terms. Such increases do not necessarily improve task performance, and may instead disrupt motor control, leading to suboptimal outcomes.

Although greater target distances can be achieved by adjusting the release angle, throwers tend to rely disproportionately on increasing velocity (Zhu et al. 2009). This tendency suggests a bias toward a velocity-dominant control strategy, even when accuracy or coordination may be compromised. Importantly, over-powering is conceptually distinct from the classical speed–accuracy tradeoff (Fitts 1954), as it reflects superfluous limb velocity production beyond biomechanical necessity, rather than a strategic prioritization of speed over accuracy. However, it remains unclear how excessive limb velocity influences motor control, particularly movement smoothness and inter-joint coordination. This limitation motivates the need for a framework that can functionally dissociate from the excessive limb velocity.

Distinguishing the required velocity from excessive velocity is nontrivial because the projectile range depends on the combined effects of release velocity, angle, and height (Linthorne 2001; Hubbard et al. 2001). Consequently, velocity cannot be evaluated in isolation. Therefore, we define over-powering relative to a physics-based benchmark that specifies the minimum velocity required for successful task completion based on a trajectory

model. Applying this framework to conditions that vary in target distance and task-goal instructions enable the dissociation of biomechanical- and strategy-driven velocity increases.

Empirical evidence indicates that adaptations to increased target distances are biased toward velocity rather than angle (Zhu et al. 2009), reflecting the underlying biomechanical constraints. In contrast, task-goal instructions directly modulate the control strategy; velocity-focused instructions substantially alter throwing kinematics, whereas accuracy-focused instructions do not reliably improve accuracy (van den Tillaar and Ettema 2003a; van den Tillaar and Aune 2019). This asymmetry suggests that task goals influence movement strategy more than outcome precision (van den Tillaar and Ettema 2006) and may even degrade accuracy when velocity is prioritized (Indermill and Husak 1984; Etnyre 1998). Together, the target distance imposes biomechanical demands, whereas task-goal instructions serve as a strategic lever that biases control toward or away from velocity dominance. Combining these two factors provides a controlled means to manipulate velocity bias, thereby eliciting and quantifying over-powering.

This velocity bias may arise from two complementary mechanisms: the biomechanical constraint and coordination conservatism hypotheses. The biomechanical constraint hypothesis posits that the effective range of release angles that yield successful trajectories are relatively narrow, thereby limiting the extent to which the distance can be modulated through angle adjustments (Linthorne 2001; Hubbard et al. 2001). Consequently, increasing velocity becomes a more reliable means of extending this range. In contrast, the coordination conservatism hypothesis suggests that large changes in the release angle may disrupt established proximal-to-distal coordination patterns. To preserve stable coordination and

avoid reorganization costs, the motor system preferentially scales limb velocity, making it a cost-effective control solution (Hirashima et al. 2003; Hirashima and Ohtsuki 2008). However, when this bias is exaggerated beyond the task requirements, it may result in over-powering.

When such excessive limb velocity is produced, the costs of over-powering are expected to reduce movement smoothness and weaken inter-joint coordination. Minimum-jerk theory predicts smoother trajectories when the jerk is minimized (Flash and Hogan 1985), whereas optimal feedback control theory predicts increased variability with larger control signals (Harris and Wolpert 1998; Todorov and Jordan 2002), thereby reducing smoothness. Jerk cost (JC) provides a quantitative index for this degradation (Nelson 1983; Aloulou and Boubaker 2016). In addition, velocity-emphasized throwing may alter the proximal-to-distal sequencing and the use of interaction torques (Hirashima et al. 2003; Hirashima and Ohtsuki 2008), potentially weakening the coordination structure. Within a principal component analysis (PCA) framework, this would be reflected in the reduced variance explained by the first principal component (PC1) (cf. Zeniya and Tanaka 2021). Together, these metrics provide theoretically grounded indices of the control efficiency and coordination structure under increased control demands.

To formalize these ideas, we introduce a two-layer definition. Velocity-dominant adjustment refers to cases in which velocity is more significant than the angle-to-distance adaptation. In contrast, over-powering is defined as a superfluous increase in velocity, instances in which angle adjustment alone would suffice to reach the target, yet additional

126 velocity is selected and identified relative to a physics-based reachability benchmark
127 specifying the minimum required velocity.

128 Based on this framework, the present study examined the following: (1) how target
129 distance and task-goal instruction influence the allocation between release angle and velocity,
130 and (2) whether over-powering is associated with motor control costs in terms of movement
131 smoothness and inter-joint coordination. We hypothesized that increasing the target distance
132 would shift control toward velocity dominance given the biomechanical constraints on the
133 release angle, and velocity-focused instructions would further amplify this tendency,
134 increasing the likelihood of over-powering. We further hypothesized that over-powering
135 would be associated with reduced movement smoothness (higher JC) and weaker inter-joint
136 coordination (lower variance explained by PC1), consistent with predictions from the
137 minimum jerk theory (Flash and Hogan 1985) and optimal feedback control theory (Harris
138 and Wolpert 1998; Todorov and Jordan 2002).

139 This study provides an operational framework for identifying and quantifying over-
140 powering in target-aimed throwing by integrating biomechanical constraints with motor
141 control strategies. By combining a physics-based benchmark of the required velocity with
142 controlled manipulations of the target distance and task-goal instructions, the framework
143 enables the dissociation between biomechanically necessary and strategy-driven velocity
144 increases. Linking over-powering to movement smoothness and inter-joint coordination
145 further reveals its motor control costs, offering new insight into how velocity-dominant
146 strategies constrain performance in goal-directed throwing.
147

2. Methods

2.1 Participants

Thirteen university students (male; age: 21–33 years, mean ± SD: 23.8 ± 3.9 years; height: 172.3 ± 5.6 cm) participated in this study after providing written informed consent. This study was approved by the Research Ethics Review Board of the authors' institution, and all procedures were conducted in accordance with the relevant guidelines and regulations.

The requisite sample size was estimated using G*Power (Faul et al. 2007) for a repeated-measures analysis of variance (ANOVA) with two within-participant factors (distances × task instruction; four conditions). Based on $\alpha = 0.05$, power $(1–\beta) = 0.80$, and an effect size of $f = 0.67$ (derived from $\eta^2_p = 0.31$, reported in previous studies on velocity–accuracy trade-off; van den Tillaar and Aune 2019), the requisite sample size was 11. Thirteen participants were recruited to account for potential data exclusion.

2.2 Apparatus

Participants performed a target-aimed throwing task in a laboratory using a tennis ball (0.06 kg) and a rectangular target (0.36 m × 0.48 m), corresponding to the standard dimensions of a baseball strike zone (Figure 1a). The lower edge of the target was positioned 0.81 m above the floor. The target surface was covered with white low-resilience polyurethane foam, and a force plate (ECG-S-1KNSA1, KYOWA, Japan) was placed beneath it to detect ball–target collisions. Two throw lines were marked on the floor at distances of 3.0 m and 4.5 m from the target.

169 The kinematic variables were recorded using spherical infrared reflective markers
170 placed on five anatomical landmarks on the throwing arm (Figure 1b): the middle fingernail
171 (finger), third metacarpophalangeal joint, ulnar styloid process (wrist), lateral humeral
172 epicondyle (elbow), and acromion (shoulder). An additional marker was placed over the
173 anterior superior iliac spine of the throwing-side pelvis. A small piece of infrared-reflective
174 tape was affixed to the center of the ball.

175 Nine infrared high-speed cameras (Prime13, OptiTrack, USA) recorded all the
176 reflective markers at 240 Hz. Three-dimensional (3D) marker coordinates were reconstructed
177 using motion capture software (Motive, OptiTrack, USA). The measurement error was less
178 than 0.5 mm. The coordinate system was defined such that the Y-axis represented the
179 direction of the ball flight, Z-axis represented the vertical direction, and X-axis was
180 orthogonal to both.

181 **2.3 Experimental design and motor task**

182 The experiment employed a 2 × 2 repeated-measures factorial design with two task-
183 goal instruction conditions (velocity-focused, V_A; accuracy-focused, A_V) and two target
184 distance conditions (3.0 m and 4.5 m). The participants performed a target-aimed throwing
185 task, attempting to hit the target using a dart-throwing motion primarily involving flexion–
186 extension of the wrist, elbow, and shoulder joints, with minimal contribution from trunk and
187 pelvic rotation.

188 To define distance conditions, a preliminary experiment was conducted with five
189 independent participants. The ball velocity at which the target was successfully hit from 3.0
190 m (mean ± SD: 9.71 ± 0.99 m/s) was measured, along with release height (1.68 ± 0.04 m)

and release angle (5.64 ± 3.31°). Using the mean release height and angle, together with the minimum ball velocity, projectile motion calculations confirmed that a ball thrown from 4.5 m at the same velocity would reach the center of the target when the release height and/or angle were appropriately adjusted. This indicates that the 4.5 m condition could be achieved without increasing the ball velocity beyond that was required at 3.0 m.

Trials for the V_A and A_V conditions were conducted in a blocked design, with the block order counterbalanced across participants. Within each block, participants performed throws from two target distances (3.0 m and 4.5 m) presented in a pseudo-randomized order.

Before the main task, the participants completed a maximum velocity test in which they were instructed to throw the ball as fast as possible toward the target from a distance of 2.5 m, without the requirement of hitting the target.

2.4 Procedures

Before the experimental sessions, the participants received standardized verbal instructions on throwing posture, including head orientation, upper body alignment, foot stance, and foot orientation. Reflective markers were then attached, after which the participants performed up to 10 practice throws to familiarize themselves with the posture and apparatus.

Following the practice phase, a maximum velocity test was conducted. Kinematic data were recorded until five trials were obtained in which participants reported exerting maximal effort.

At the beginning of each V_A and A_V block, participants were provided with written instructions. In the V_A (velocity-focused) condition, they were instructed: “Your goal is to

throw the ball as fast as possible. Also, try to hit the target." In the A_V (accuracy-focused) condition, they were instructed: "Your goal is to throw the ball to hit the target. Also, try to throw the ball fast."

The participants performed 10 practice throws at each target distance, followed by a one-minute rest period. They then completed 10 test trials per distance, resulting in a total of 40 trials per participant (2 distances × 2 instruction conditions × 10 trials).

2.5 Measurements and data analysis

All the data analyses and statistical tests were performed using MATLAB R2025a (MathWorks, Natick, MA, USA).

2.5.1 Release parameters

The original 3D marker coordinates were resampled at 960 Hz using a cubic spline interpolation. The ball release was defined as the time point at which the relative velocity between the finger and ball markers along the Y-axis exceeded 2.0 m/s.

To evaluate angular velocity allocation, three release parameters were computed for each trial: (1) release velocity, or the scalar velocity of the ball in the Y–Z plane at release; (2) release angle, or the pitch angle of the velocity vector in the Y–Z plane; and (3) release height, or the Z-coordinate of the ball at release.

2.5.2 Reachability simulation

As distance adaptation involves coordinated changes in release velocity, angle, and height, it is not self-evident whether an observed velocity increase is functionally necessary or superfluous; this depends on whether angle and height adjustments alone could compensate for the increased distance. To test whether increasing the release angle alone

would allow the ball to reach the 4.5 m target while maintaining the same release velocity used for the 3.0 m target, we conducted a post-hoc reachability simulation based on ball-flight dynamics. The simulation was only applied to successful trials (hits) because the ball height at the target plane could not be determined for misses.

A two-dimensional (Y–Z) trajectory model incorporating aerodynamic drag was used. The drag force was assumed to be proportional to the square of the ball velocity.

$$F_{drag} = \frac{1}{2}\rho C_D A|v|^2$$

where ρ is air density, C_D is the drag coefficient, A is the cross-sectional area of the ball, and $|v|$ is the magnitude of the ball velocity. The equations of motion in the Y- and Z-directions are given by

$$\frac{d^2y}{dt^2} = -\frac{1}{2m}\rho C_D A\, v_Y \sqrt{v_Y^2 + v_Z^2}$$

$$\frac{d^2z}{dt^2} = -g - \frac{1}{2m}\rho C_D A\, v_Z \sqrt{v_Y^2 + v_Z^2}$$

where m is the ball mass and g is the gravitational acceleration. The equations were numerically integrated using a MATLAB ODE solver (ode45) with state vectors. The initial conditions were defined based on measured release parameters.

For each participant and task-goal instruction condition, successful trials at the 4.5 m target distance were analyzed. For each trial, the observed release height was used together with the mean initial ball velocity components (,) derived from successful trials at the 3.0 m target distance. The pitch angle was systematically varied from 0° to 45° in 0.1° increments to determine the minimum angle required for the simulated trajectory to reach the center of

255 the target zone (= 0.81 + (1.29 − 0.81)/2 m) at the 4.5 m target distance. A trajectory was
256 considered successful when the ball height at the target plane matched the target center.
257 *2.5.3 Performance measurements*
258 The maximum velocity obtained across five trials was defined as the maximal
259 performance of each participant. Velocity control was quantified as the ratio of ball velocity
260 in each trial to the maximum value, expressed as a percentage (%Vmax), and averaged across
261 trials within each condition.
262 The accuracy performance was quantified as the hit rate (% Hit), defined as the
263 percentage of successful trials (n = 10) in which the target was hit for each condition. To
264 normalize the proportional data, the % Hit values were arcsine-transformed. Values of 0 and
265 1 were adjusted to 0.25/n and (n − 0.25)/n, respectively, following Mori and Yoshida (1990).
266 *2.5.4 Kinematic measurements*
267 The time series of the 3D marker coordinates were smoothed using a fourth-order
268 Butterworth low-pass filter with a cutoff frequency of 6 Hz. The filtered data were used to
269 compute the joint angles at the wrist, elbow, and shoulder in the Y–Z plane. Each joint angle
270 time series was fitted with a fourth-order spline function, and its first derivative was used to
271 compute joint angular velocities.
272 Two motion phases were defined relative to the ball release: forward swing (pre-
273 release) and follow-through (post-release) (Figure 1b). A representative example of the joint
274 angle and angular velocity time series is shown in Figure 2. The start of the forward swing
275 (SF) was defined as the instant when the elbow extension angular velocity exceeded 5% of
276 its maximum value during the throw. The end of the follow-through (EF) was defined as the

277 instant when the elbow extension angular velocity dropped below 5% of its maximum value
278 after ball release.
279 *2.5.5 Principal component analysis*
280 Independent PCAs were performed for each participant and experimental condition,
281 yielding a total of 52 analyses (13 participants × 2 task-goal instruction conditions × 2 target
282 distances). For each dataset consisting of a time series of joint angular velocities (wrist,
283 elbow, and shoulder) from the SF to EF, the data were time-normalized to 100 points using
284 cubic spline interpolation. The normalized time points were treated as samples and the joint
285 angular velocities across 10 trials were treated as variables (30 variables = 3 joints × 10 trials).
286 PCA was applied to the variance–covariance matrix of each dataset.
287 As the cumulative variance explained by the first two principal components (PC1 and
288 PC2) exceeded 80% in all cases, only these two components were retained (Table 1). The
289 percentages of explained variance for PC1 (% VEpc1) and PC2 (% VEpc2) were used as
290 dependent variables in the subsequent analyses.
291 The PC1 scores exhibited a single-peaked, bell-shaped velocity profile consistent with
292 the group-averaged curves (Figure 3a). Accordingly, the peak PC1 score was extracted for
293 each participant and used as an additional dependent variable.
294 *2.5.6 Jerk cost*
295 JC was calculated from the original time series of joint angles (wrist, elbow, and
296 shoulder) from SF to EF based on the method proposed by Nelson (1983). Each joint angle
297 time series was fitted using a sixth-order spline function and its third derivative was used to
298 compute the jerk time series [j(t)]. JC was defined as:

$$JC = dt$$

where T represents the movement time from SF to EF.

For each joint, the JC values were averaged across the 10 trials within each condition for each participant. Lower JC values indicate smoother movements, whereas higher values indicate less smooth (jerkier) movements.

2.5.7 Statistical analysis

Anderson–Darling tests indicated no significant deviations from normality for % Vmax, arcsine-transformed % Hit, maximum PC1 score, elbow JC, or the three release parameters (release velocity, angle, and height) ($p > .05$). For these variables, a two-way repeated-measures ANOVA was conducted with task-goal instructions (V_A, A_V) and target distance (3.0 m and 4.5 m) as within-participant factors. When the assumption of sphericity was violated, the Greenhouse–Geisser correction was applied. Effect sizes were quantified using generalized eta squared (η^2G) (Bakeman 2005).

Given their skewed distributions of % VEpc1, % VEpc2, and JC values of the wrist and shoulder joints, pairwise Wilcoxon signed-rank tests were used as nonparametric alternatives to repeated-measures ANOVA. Separate tests were conducted to examine the effects of the task-goal instruction and target distance. The effect size was quantified using r, calculated as the Z-statistic divided by the square root of the sample size. A Bonferroni-corrected significance threshold ($p < .05/2$) was used to account for multiple comparisons.

For the reachability simulation, the within-participant mean of the simulated minimum pitch angle was compared to the mean observed pitch angle at the 4.5 m target distance. The difference (observed vs. simulated) was tested against zero using a one-sample t-test for each

task-goal instruction condition. A negative difference indicates that the ball velocity used at 3.0 m would have been insufficient to reach the 4.5 m target center, whereas a non-significant difference indicates that it would have been sufficient.

3. Results

3.1 Effects on release parameters

Figure 4 shows the group means and standard errors of the three release parameters. For release velocity, significant main effects were found for both target distance ($F(1,12) = 7.23$, $p = .020$, $\eta^2G = .029$) and task-goal instruction ($F(1,12) = 25.58$, $p < .001$, $\eta^2G = .151$), where velocity increased for the 4.5 m distance and under the velocity-focused instruction. No significant interaction was observed ($F(1,12) = 1.16$, $p = .303$, $\eta^2G = .001$).

For release angle, a significant main effect of target distance was found ($F(1,12) = 81.24$, $p < .001$, $\eta^2G = .313$), where the release angle for the 4.5 m target was greater than the 3.0 m one. However, neither the main effect of task-goal instruction ($F(1,12) = 2.96$, $p = .111$, $\eta^2G = .018$) nor the interaction ($F(1,12) = 0.59$, $p = .459$, $\eta^2G = .002$) was significant.

For release height, a significant main effect of target distance was found ($F(1,12) = 117.78$, $p < .001$, $\eta^2G = .069$), where release height increased for the 4.5 m target. Neither the main effect of task-goal instruction ($F(1,12) = 2.17$, $p = .167$, $\eta^2G = .001$) nor the interaction ($F(1,12) = 1.08$, $p = .318$, $\eta^2G < .001$) was significant.

In summary, increasing the target distance led to adjustments in all three release parameters, whereas the task-goal instruction selectively influenced release velocity without significantly affecting the release angle or height. These results indicate that distance

adaptation was achieved through coordinated modulation of multiple release parameters, whereas task-goal instruction primarily influenced velocity control.

3.2 Reachability analysis

To assess whether the velocity at 3.0 m was sufficient for the 4.5 m target, a reachability simulation was conducted. The reachability simulation yielded different patterns across task-goal instruction conditions.

In the A_V condition, the difference between observed and simulated minimum pitch angle was significantly below zero ($t(12) = -2.47$, $p = .030$; 95% CI [−2.70, −0.17]), indicating the observed pitch angle, on average, was smaller than the simulated minimum.

In the V_A condition, this difference did not significantly differ from zero ($t(12) = -1.11$, $p = .290$; 95% CI [−2.65, 0.86]), with the confidence interval, including zero, indicating that the observed pitch angle did not differ significantly from the simulated minimum on average.

3.3 Effects on performance

Figure 5 shows the group means and standard errors for %Vmax and %Hit. For % Vmax, significant main effects were found for both target distance ($F(1,12) = 9.40$, $p = .010$, $\eta^2G = .037$) and task-goal instruction ($F(1,12) = 28.40$, $p < .001$, $\eta^2G = .159$), where %Vmax increased as target distance increased, and was higher in the V_A condition than in the A_V condition. No significant interaction was observed ($F(1,12) = .02$, $p = .886$, $\eta^2G < .001$).

For %Hit, a significant main effect of target distance was found ($F(1,12) = 4.9$, $p = .048$, $\eta^2G = .068$), where % Hit decreased as target distance increased. Neither the main effect of task-goal instruction ($F(1,12) = 2.50$, $p = .139$, $\eta^2G = .028$) nor the interaction ($F(1,12) = 1.00$, $p = .335$, $\eta^2G = .012$) were significant.

3.4 Effects on inter-joint coordination

Figure 3b shows the group means and standard errors of the maximum PC1 scores. A significant main effect of target distance was found ($F(1,12) = 12.40$, $p = .004$, $\eta^2G = .026$), where maximum PC1 score increased as target distance increased. A significant main effect of task-goal instruction was also found ($F(1,12) = 39.6$, $p < .001$, $\eta^2G = .148$), with higher values in the V_A condition than in the A_V condition. No significant interaction was found ($F(1,12) = 1.25$, $p = .285$, $\eta^2G = .001$).

Table 1 presents the explained variance in PC1 and PC2. For %VEpc1, a significant effect of target distance was found under the V_A condition (4.5 m < 3.0 m, $Z = 2.80$, $p = .006$, $r = .77$), whereas no such effect was observed under the A_V condition ($Z = .20$, $p = .860$, $r = .05$). Task-goal instruction had no significant effect at either 3.0 m ($Z = .10$, $p = .917$, $r = .03$) or 4.5 m ($Z = 1.40$, $p = .173$, $r = .38$).

For %VEpc2, a significant effect of target distance was found under the V_A condition (3.0 m < 4.5 m, $Z = -2.80$, $p = .006$, $r = -.77$), but not under the A_V condition ($Z = 0.60$, $p = .553$, $r = .17$). No significant effects of task-goal instruction were observed at either 3.0 m ($Z = 0.70$, $p = .463$, $r = .20$) or 4.5 m ($Z = -1.50$, $p = .133$, $r = -.42$).

3.5 Effects on smoothness

Figure 6 shows the mean values and standard errors of JC for each joint. For the wrist joint, no significant differences were observed between the target distances in either the A_V condition ($Z = 0.04$, $p = .972$, $r = .01$) or the VA condition ($Z = 1.40$, $p = .152$, $r = .40$). No significant differences were observed between task-goal instruction conditions at either 3.0 m ($Z = 1.50$, $p = .133$, $r = .42$) or 4.5 m ($Z = 1.10$, $p = .279$, $r = .30$).

For the elbow joint, a significant main effect of throwing distance was found ($F(1,12) = 9.30$, $p = .010$, $\eta^2G = .088$), where JC increased as the target distance increased. Neither the main effect of task-goal instruction ($F(1,12) = 3.70$, $p = .080$, $\eta^2G = .065$) nor the interaction ($F(1,12) = 0.60$, $p = .473$, $\eta^2G = .004$) was significant.

For the shoulder joint, significant differences between target distances were found in both the AV condition (3.0 m < 4.5 m, $Z = -3.00$, $p = .003$, $r = -.82$) and the V_A condition (3.0 m < 4.5 m, $Z = -2.50$, $p = .013$, $r = -.69$). At 3.0 m, JC was significantly higher in the V_A condition than in the A_V condition ($Z = 3.00$, $p = .002$, $r = .84$), whereas no significant difference was observed between conditions at the 4.5 m ($Z = -1.00$, $p = .100$, $r = -.46$).

4. Discussion

This study provides evidence that velocity production in target-aimed throwing is systematically modulated by both biomechanical and strategic factors, and introduces a quantitative framework to dissociate their contributions.

With respect to the first aim, increasing the target distance led to coordinated adjustments in release velocity, angle, and height, whereas the task-goal instruction selectively influenced release velocity without significantly affecting angle or height. This asymmetry suggests that distance adaptation involves multiparameter coordination (Linthorne 2001; Hubbard et al. 2001), whereas task-goal instruction primarily modulates the magnitude of the motor output.

Reachability analysis revealed that increases in velocity under an accuracy-focused condition were biomechanically necessary, whereas those under a velocity-focused condition

409 could, at least in part, be interpreted as superfluous, consistent with over-powering and its
410 predicted motor control costs under signal-dependent noise (Harris and Wolpert 1998;
411 Todorov and Jordan 2002).

412 Regarding the second objective, increases in the peak magnitude of PC1 were
413 associated with reduced movement smoothness, as reflected by the higher jerk costs at the
414 elbow and shoulder. In addition, under the velocity-focused condition at a longer distance,
415 where this increase was the greatest, the inter-joint coordination was weakened, as indicated
416 by the lower variance explained by PC1.

417 **4.1 Mechanisms of velocity-dominant adjustment**

418 Our study's findings suggest that limb velocity-dominant adjustment in target-aimed
419 throwing arises from the distinct control mechanisms underlying distance-driven adaptation
420 and task-goal-dependent modulation.

421 When the target distance increased, the throwers adjusted multiple release parameters,
422 with the release angle showing the largest effect. This indicates that distance adaptation is
423 primarily achieved through the modulation of spatial parameters (Leigh et al. 2010), which
424 is consistent with the biomechanical constraint mechanism (Linthorne 2001; Hubbard et al.
425 2001), whereby the angle is tuned within a limited functional range to satisfy task demands,
426 and velocity is recruited only when further adjustment is required (Linthorne and Everett
427 2006).

428 In contrast, task-goal instructions produced a qualitatively different pattern. Velocity
429 emphasis selectively increased the release velocity without significantly altering the release
430 angle or height, suggesting that the spatial configuration of the movement was preserved.

This pattern is consistent with the coordination conservatism mechanism, in which existing proximal-to-distal synergies are maintained and task demands are accommodated through gain-scaling of motor output (Hirashima et al. 2003; Hirashima and Ohtsuki 2008), rather than reconfiguration of spatial parameters.

Together, these findings indicate that a velocity-dominant adjustment does not simply reflect biomechanical necessity but can emerge from the top-down modulation of output gain imposed on a conserved coordination structure. In such cases, increases in limb velocity may be independent of spatial requirements, raising the possibility that some portion of the limb velocity increase is not functionally required.

4.2 Identification of over-powering using reachability

The reachability benchmark provides a functional criterion for determining whether the observed increases in the release velocity are biomechanically necessary or superfluous. Under the accuracy-focused condition, the observed release angles at the 4.5 m target were significantly smaller than the simulated minimum angle. This indicates that the baseline velocity observed at 3.0 m was insufficient to reach the center of the 4.5 m target; thus, the increase in velocity can be interpreted as at least partly necessary to satisfy task constraints.

In contrast, under the velocity-focused condition, the observed release angles at the 4.5 m target did not significantly differ from the simulated minimum angle. Although this null result does not conclusively establish sufficiency, it is consistent with the possibility that the increased distance could have been accommodated through angular adjustment alone without requiring additional velocity. Given that the baseline velocity already corresponded to

approximately 90% of the maximal velocity, the additional increase observed at 4.5 m was unlikely to be strictly necessary.

Overall, these results demonstrate that reachability analysis enables the dissociation between biomechanically necessary and superfluous velocity increases. While the velocity increases under the accuracy-focused condition appear to be functionally required, those observed under the velocity-focused condition are consistent with superfluous increases in velocity production. Within the present framework, unnecessary velocity increases were defined as over-powering.

4.3 Motor-control costs of over-powering

These results suggest that over-powering is associated with measurable motor control costs, as reflected in both reduced movement smoothness and weakened inter-joint coordination. Greater increases in movement output, as indexed by the peak magnitude of PC1, were associated with higher jerk costs at the elbow and shoulder, indicating reduced smoothness (Flash and Hogan 1985). This pattern suggests that amplifying motor output may disrupt the temporal regularity of movement, deviating from smoother trajectories.

In addition, under the velocity-focused condition at a longer distance, where the velocity increases were likely superfluous, the inter-joint coordination was weakened, as indicated by the lower variance explained by PC1 (Thomas et al. 2005; Zeniya and Tanaka 2021). This finding implies that an excessive output may also compromise the stability of the coordinated joint patterns, particularly when the velocity is increased beyond the task requirements.

Importantly, these increases in movement output were not accompanied by improved task performance (van den Tillaar and Ettema 2003a, b). Although target accuracy, indexed by hit rate, decreased with increasing distance, task-goal instructions did not significantly affect target accuracy, despite producing substantial increases in velocity. This pattern suggests that the additional velocity generated under the velocity-focused condition does not confer a performance advantage, although it is associated with increased motor control costs.

These findings are broadly consistent with predictions from the minimum jerk (Flash and Hogan 1985) and optimal feedback control theories (Harris and Wolpert 1998; Todorov and Jordan 2002), which posit that efficient movement emerges from the minimization of control-related costs under task constraints. From this perspective, over-powering may reflect a deviation from cost-efficient control, in which the velocity is increased without full consideration of its impact on movement quality or task performance.

Overall, these results indicate that over-powering is associated with identifiable motor control costs without clear performance benefits, highlighting the tradeoff between increased output and movement efficiency.

4.4 Limited effect of accuracy-focused task-goal instruction

Although the accuracy focused instruction reduced ball velocity, it did not significantly improve accuracy. This finding is consistent with previous studies showing that emphasizing accuracy does not necessarily enhance accuracy performance (van den Tillaar and Ettema 2003a, b, 2006).

Two factors may have accounted for this limited effect. First, the influence of the target distance may have outweighed that of task-goal instruction. Because target distances were

alternated in a randomized order, participants likely adjusted their output primarily in response to the perceived distance (Zhu et al. 2009), thereby reducing the impact of verbal instructions.

Second, reducing velocity does not necessarily simplify the control demands of the task. From a projectile mechanic perspective, slower throws require a steeper trajectory to reach the target, increasing the sensitivity to release timing and angle (cf. Linthorne 2001). Additionally, movements performed below the submaximal velocity may exhibit greater variability (Urbin et al. 2012). Together, these factors may offset any potential accuracy benefits of velocity reduction. This suggests that simply improving accuracy may be insufficient to improve performance without corresponding changes in task constraints or control strategies.

4.5 Limitations and future directions

This study had several limitations. First, the sample size was relatively small and limited to non-athletes. Future studies should examine whether susceptibility to over-powering varies according to expertise and psychological factors. Second, the task involved a simplified joint structure compared to full-body throwing movements. Extending this framework to include more complex actions may reveal additional coordination dynamics. Third, the reachability analysis was restricted to successful trials, which may limit generalizability. Incorporating trajectory measurements from all trials would provide a more complete assessment. Finally, integrating electromyographic data could clarify neuromuscular mechanisms, such as co-contraction (Osu et al. 2002), underlying reduced smoothness in over-powering.

5. Conclusion

The present study demonstrates that velocity production in target-aimed throwing is shaped by both biomechanical constraints and task-goal-dependent modulation, which operate through distinct control mechanisms. By introducing a reachability-based framework, this study distinguishes between biomechanically necessary and superfluous increases in velocity; the latter is defined as over-powering.

Importantly, over-powering was associated with measurable motor control costs, including reduced movement smoothness and weakened inter-joint coordination, without corresponding improvements in task performance. These findings suggest that increases in motor output are not always functionally beneficial and may reflect inefficient control strategies in some cases. Overall, this framework provides a basis for identifying and interpreting excessive velocity production in goal-directed actions and may contribute to a better understanding of the efficiency and adaptability of human motor control.

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Table

Table 1 The cumulative variance explained by PC1 and PC2 for the task goal instructions and throwing distances

*$p < .05$

Task goal		3.0 m			4.5 m							
PC1		*Mean*	*SD*	*95%CI*	*Mean*	*SD*	*95%CI*	*df*	*p*		*z*	*es*
	A_V	85.9	5.28	82.7-89.1	85.1	7.02	80.9-89.3	12	0.8613		0.1747	0.0485
	V_A	86.1	7.06	81.8-90.4	84.3	6.76	80.2-88.4	12	0.0057	*	2.7604	0.7656
PC2		*Mean*	*SD*	*95%CI*	*Mean*	*SD*	*95%CI*	*df*	*p*		*z*	*es*
	A_V	9.55	5.43	6.27-12.8	10.81	6.92	6.63-15.0	12	0.5525		-0.594	-0.1647
	V_A	10.07	6.72	6.01-14.1	11.68	7.17	7.35-16.0	12	0.0057	*	-2.7604	-0.7656

Figure captions

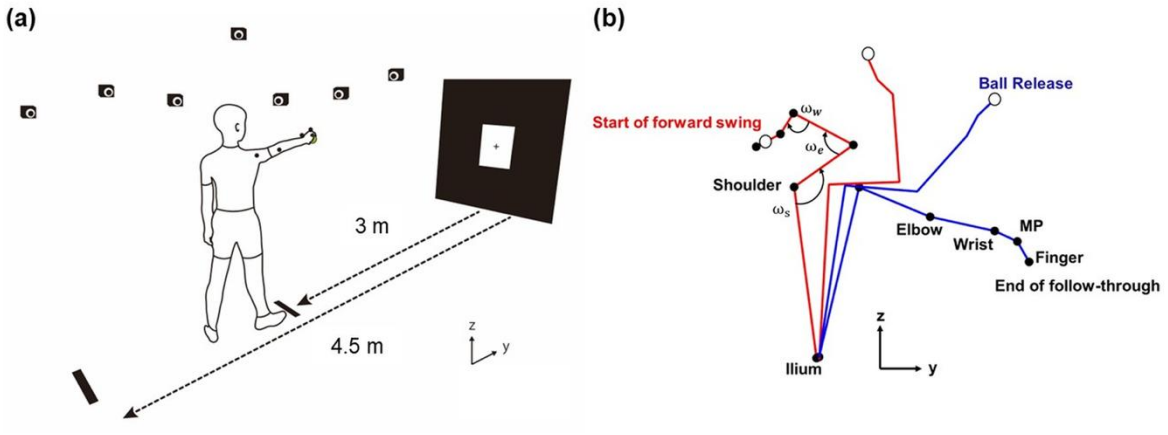
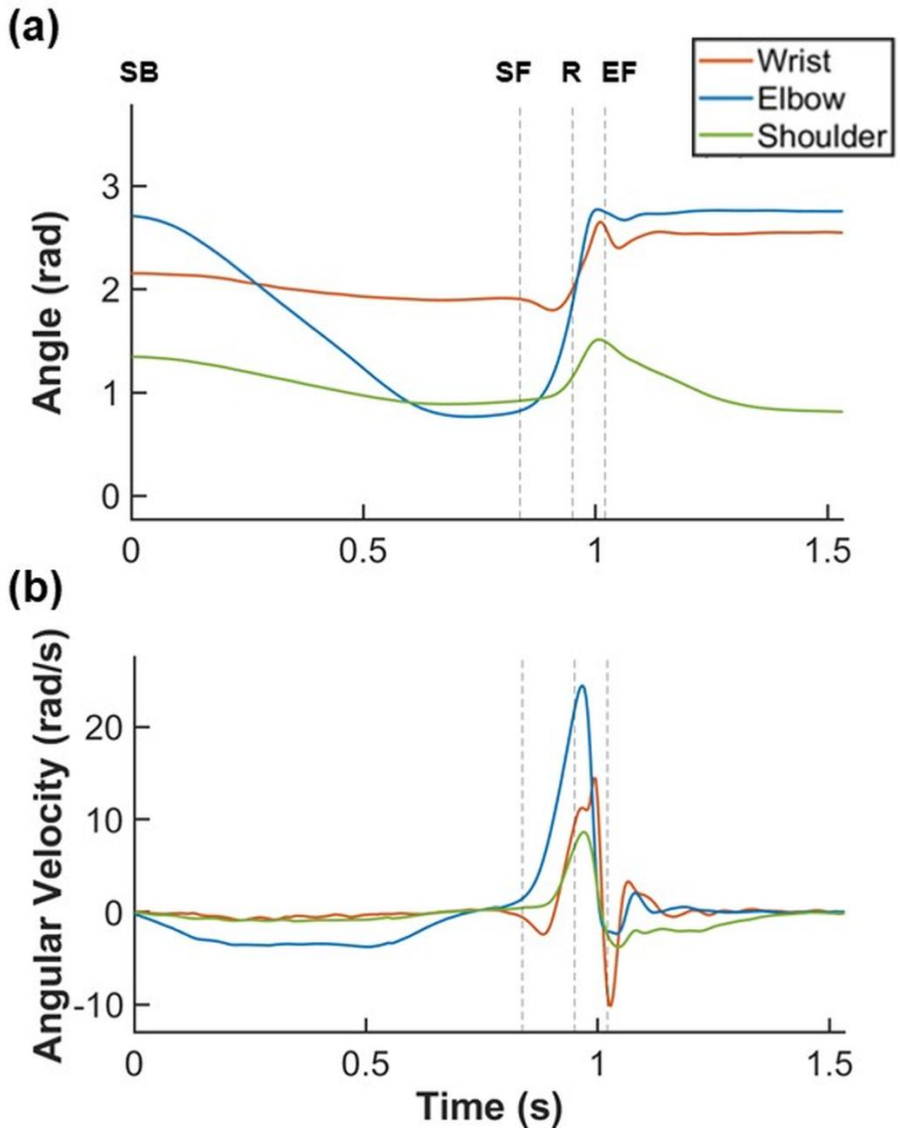


Fig. 1 (a) Experimental setup. (b) Stick figures represent the segmentation of arm swings. The positive Y-direction corresponds to the ball flight path. *ωw*, *ωe*, and *ωs* with arrows indicate the extension velocity of the wrist, elbow, and shoulder joints, respectively. MP refers to the metacarpophalangeal joint. Red and blue sticks illustrate arm postures during the forward swing phase and follow-through phase, respectively.



637

638 **Fig. 2** A typical example of time series data of angle (a) and angular velocity (b) at the wrist,
639 elbow, and shoulder joints of the throwing arm. The origin of the time axis corresponds to
640 the start of the backward swing (SB). The three dashed lines indicate the start of forward
641 swing (SF), the ball release (R), and the end of the follow-through (EF).

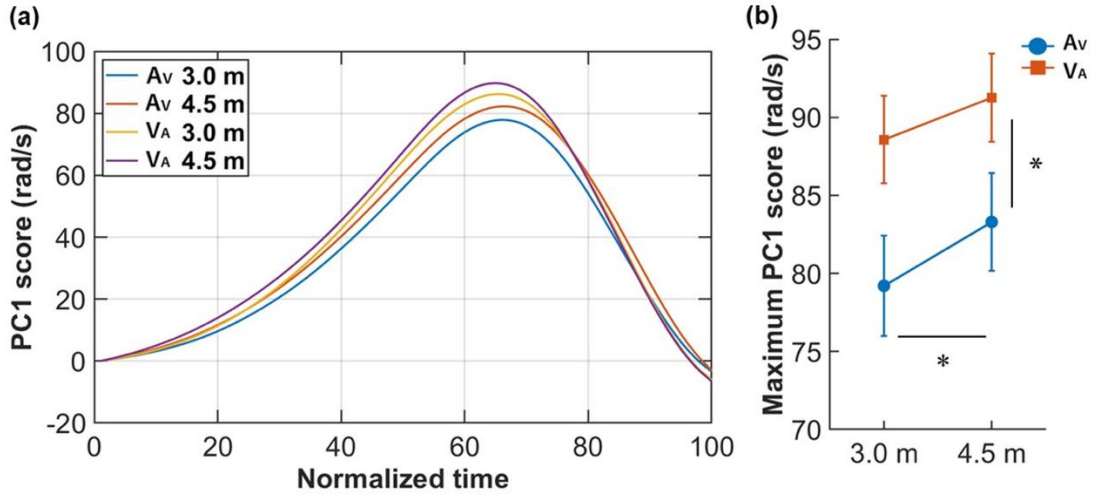


Fig. 3 The group-averaged composite angular velocity profile derived from PC1 (a). Comparisons of the maximum PC1 score across task-goal instructions as a function of throwing distance (b). The error bars represent standard errors. * Indicates a significant main effect in ANOVA ($p < .05$).

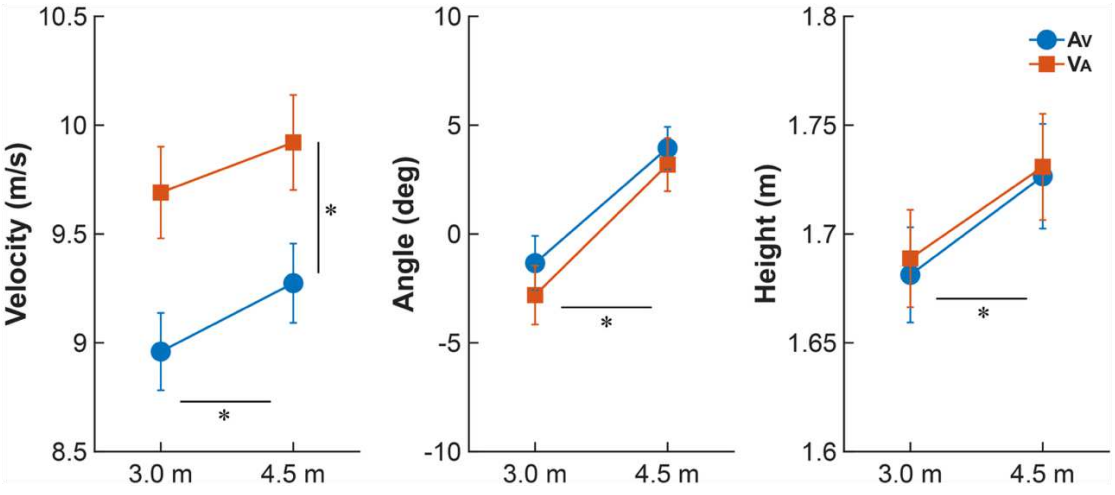


Fig. 4 Group means and standard errors of the three release parameters across task-goal instructions as a function of throwing distance. * Indicates a significant main effect in ANOVA ($p < .05$).

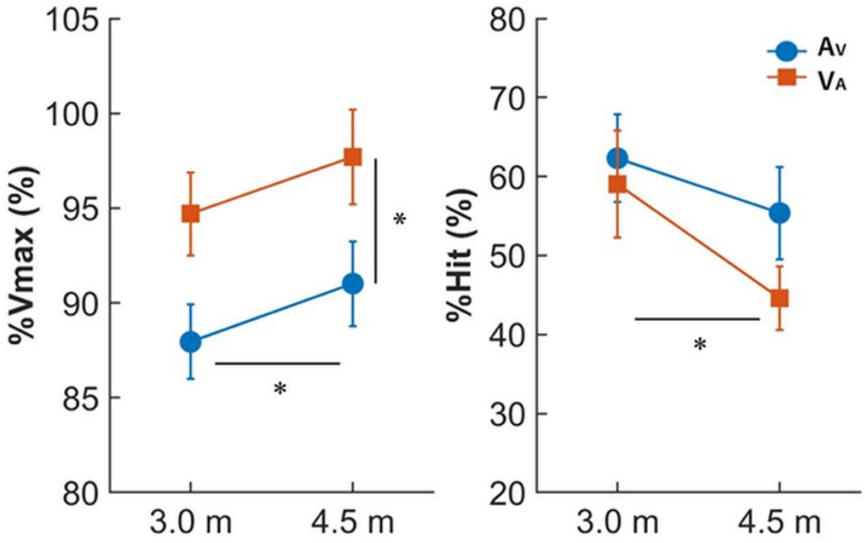


Fig. 5 Group means and standard errors of the performance measurements across task-goal instructions as a function of throwing distance. * Indicates a significant main effect in ANOVA ($p < .05$).

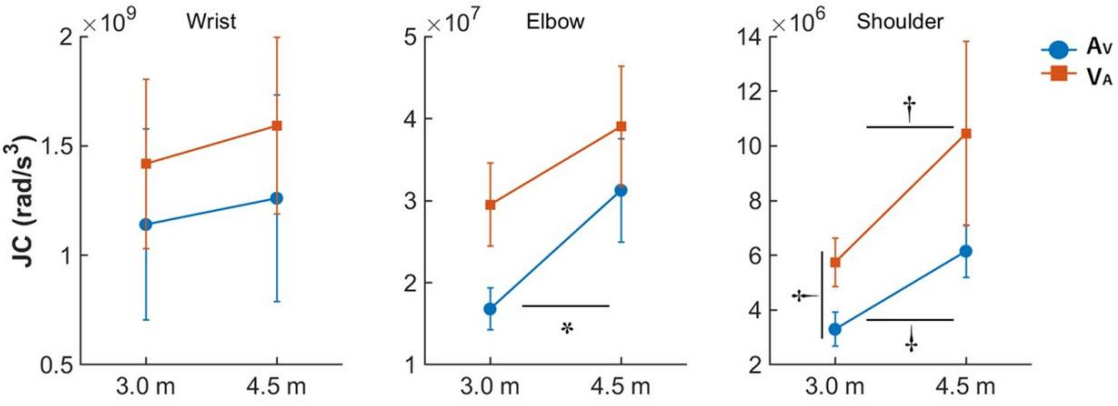


Fig. 6 Group means and standard errors of jerk cost (JC) across task-goal instructions as a function of throwing distance. Higher JC values indicate reduced smoothness of arm swing movement. * Indicates a significant main effect in ANOVA, and † indicates a significant difference in Wilcoxon signed-rank tests ($p < .05$).