Received: 19 August 2021 | Revised: 4 August 2022 | Accepted: 5 September 2022

DOI: 10.1111/sms.14233

ORIGINAL ARTICLE

WILEY

Segmental sequencing of the upper body segments in unconstrained maximum overarm throws: An implication for coaching

Allan Chak Lun Fu[1] | **Stephen Paul Cobley**[2] | **Ross Howard Sanders**[2]

[1]Discipline of Physiotherapy, Faculty of Medicine and Health, the University of Sydney, Sydney, New South Wales, Australia

[2]Discipline of Exercise and Sport Science, Faculty of Medicine and Health, the University of Sydney, Sydney, New South Wales, Australia

Correspondence
Allan Chak Lun Fu, Discipline of Physiotherapy, Faculty of Medicine and Health, the University of Sydney, Sydney, Australia.
Email: allan.fu@sydney.edu.au

Overarm throwing is an essential fundamental movement skill (FMS). Competency in throwing is critical to encourage physical activity throughout lifespan. However, the segmental sequencing characteristics of skilled throwing to achieve maximum ball release speed are unclear. Further, the standard instructions for segmental sequencing in coaching manuals are anecdotal and not based on scientific evidence. Therefore, the aim of this study was to establish the critical features of upper-body sequencing in skilled throwing for maximum speed. This would enable revised instructions for coaching throwing based on scientific evidence. The three-dimensional kinematics of 144 right-handed unconstrained maximum overarm throws were captured and analyzed. The quartiles of participants with the fastest and lowest ball release speed, normalized by height, were defined as the Skilled Group and Less Skilled Group, respectively. Paired *t*-tests were used to determine the differences in times of successive events within groups and independent *t*-tests for between-group differences in temporal space between events for all sequences. A characteristic segmental sequence of each group was defined as a sequence with significant within-group differences in two successive events ($p < 0.001$), while a critical segmental sequence was defined as a sequence with significant differences in temporal space both within groups and between groups ($p < 0.001$). The Skilled Group had six characteristic sequences, while two were found for the Less Skilled Group, summarized in the conceptual model. A single critical sequence of non-throwing arm elbow extension prior to shoulder extension was found. Five evidence-based instructions were recommended to add to the Australian FMS instruction manual.

KEYWORDS

fundamental movement skills, kinetic link principle, motor competency, overarm throwing, physical education

1 | INTRODUCTION

Fundamental movement skills (FMS) are goal-directed movement patterns that impact individual capability to be physically active across the lifespan.[1,2] Unconstrained overarm throwing is a key FMS to build coordinative movements, encourage sports participation, and enable physical activity (PA).[1,3] Early adolescents (around 10–14) are expected to acquire 14 critical kinematic features in unconstrained overarm throwing without further training.[4] These features are distinct from sports-specific overarm throws constrained by the environment rules and instructions.[4] Low skill level is likely to delay the development of sport-specific skills such as baseball or cricket, or throw-like activities required for lifetime PA.[1,5] Understanding the segmental sequencing of body segments in throws for maximum release speed, a reflection of motor competency, can inform clinicians and coaches to coach effectively to improve performance,[6,7] prevent injuries,[8] and identify talent.[9] This is particularly crucial for early adolescents as middle childhood (aged 6–8 years) has five flexible developmental stages in overarm throwing,[10] which are likely to interfere with segmental sequencing in early adolescents. Further, the level of motor competency is strongly and positively associated with PA levels.[3,11] Therefore, having coordinated segmental sequencing in overarm throwing is essential from a public health perspective to help prevent non-communicable diseases and low health trajectories.

Although there is a body of evidence pointing toward the "existence of proximal-to-distal segmental sequencing" in throwing activities,[6–8,12–22] the characteristics of segmental sequencing in overarm throws as FMS are not fully understood.[21] According to the traditional "summation of speed principle"[23] and "Kinetic Link Principle,"[24] an effective and coordinated movement pattern in throwing should involve proximal-to-distal sequence from larger body segments to smaller body segments (e.g., from upper trunk rotation to humerus internal rotation). Prior investigations of segmental sequencing were not comprehensive with respect to including all the rotations of the upper body and throwing arm..[6–8,17,18,22,25,26] For example, Oyama et al.[8] analyzed only the rotation sequence of the shoulder and pelvic girdles. Reid et al. and Wagner et al.[6,18]investigated the pelvic and upper girdles and all the peripheral joints in the throwing arm. In addition to analyzing the trunk and the throwing arm, Beach[7] and van den Tillaar and Ettema[17] examined the hip and knee joints. However, none of these studies investigated the contributions of segmental sequencing of all upper body segments to maximum ball release speed in unconstrained conditions (i.e., FMS). Murata[27] reported that skillful pitchers, who had a faster ball release speed, had less shoulder joint linear displacement in their non-throwing arm than the less skilled pitchers during their maximum throws toward a home plate. Further, the smaller the shoulder joint, the faster the ball release speed. Hong et al.[12] concluded that the trunk anticlockwise rotation and shoulder internal rotation of the right handers happened almost simultaneously during a maximum pitch and thus no proximal-to-distal rotational sequence; however, the study was based on a very small sample size ($n = 3$). Ishida and Hirano[26] tested the effect of the non-throwing arm movements on the throwing arm by constraining the movements of the non-throwing arm in an abducted position using long rubber bands. The timing of maximum pelvic angular velocity in the anticlockwise rotation was achieved earlier in the constrained condition than the unconstrained condition. Van den Tillaar and Ettema compared the differences in overarm throwing between dominant and non-dominant arms.[28] Despite the segmental sequences of the contralateral non-throwing arm not being investigated, the between-arm differences in maximum joint angular velocity and onset of joint movement imply different movement strategies were utilized between arms. All these indicated that the non-throwing arm movements are related to the temporal characteristics of other body segments, including the throwing arm.

The instructions in the existing coaching manuals for throwing relating to segmental sequencing are limited,[29–31] and little scientific evidence is available from these descriptions. One of the most detailed instruction manuals was published by the Department of Education Western Australia.[29] The only segmental sequencing instruction relating to the movements of the upper body is that pelvic girdle rotation is followed by upper girdle rotation. This instruction is based on a qualitative theoretical approach to motor development such as Component Stage Theory[32] and laterally transferred from descriptions of sports-specific throwing patterns in lay documents,[2,29–31] and henceforth, hinder the development of sport expertise. However, based on the "Kinetic Link Principle," there should be more than one segmental sequence in the upper body to maximize speed of ball release. To the authors' knowledge, no studies have been conducted to assess the characteristics of segmental sequencing in the upper body at different skill level. Failure to instruct appropriate foundational overarm throwing skill criteria is likely to compromise learning efficiency and throwing competency, widenening the skill-learning gap for peers of similar age, and henceforth, hinder the sport expertise development.[33]

We hypothesized that the segmental sequencing features of maximum overarm throwing speed were different between "skilled" and "less skilled" adolescents. Consequently, the aim of this study was to identify the features of "skilled" and "less skilled" sequence of joint and segment rotations of the upper body for maximum ball release speed in unconstrained overarm throws. Such findings can inform clinicians, coaches, and physical educators to help inform assessment, practice, and determine the appropriateness of current coaching manuals.

2 | MATERIALS AND METHODS

2.1 | Participants

Following institutional ethical approval (Case No: 2015/818), parent and pupil consent, 305 year 7 students, aged 13.04 (±0.35) from a sports high school in Sydney, Australia, were invited to participate. Approximately half of the students were actively participating in sports team training, while half were normally developing adolescents not involved in sports training. This setting ensured that adolescents with a spectrum of skill levels were recruited. Participants were excluded if their movements were affected by visual deficits not corrected by glasses, apparent leg length discrepancy, pain, injuries, or surgeries. Seventy-nine parents did not permit their child's participation, and 72 eligible participants declined participation during the data collection period due to personal reasons. Ultimately, 144 "right-handed" throwers (41 males and 31 females) and 10 "left-handed throwers" (seven males and three females) participated. However, only the performance of the right-handed throwers was analyzed.

2.2 | Data collection

Participants were tasked with throwing a standard baseball with maximum release speed to a net hanging vertically four meters away from the point of release to arrest the ball motion. All demographic, anthropometric, and kinematic data were collected in the university biomechanics laboratory. An accredited anthropometrist first collected demographic and anthropometric data. Data collected were age, sex, height, weight, and hand dominance. Body mass index was derived as the weight (kg) divided by the square of the height (m).

Following a 5-min warm-up and practice, reflective markers (Supplementary material S1) were adhered to various anatomical landmarks to form an 8-segment kinematic model to analyze upper body movements including the pelvic girdle, upper girdle, bilateral humerus, bilateral forearm, and bilateral hand segments. A baseball, which was considered a suitable size and weight for adolescents to fully control, was covered with reflective tape and resembled a marker. To capture the throwing motion, a 14-camera motion analysis system (Cortex Version 6.0, Motion Analysis Corporation, USA) sampling at 100 Hz with a residual error <0.5 mm was employed. The testing area was 12 m × 8 m with a capture volume of 4 m × 3 m × 2.5 m. Participants chose any starting position within the testing area (i.e., stationary or an approach was allowed) and threw without any constraints, rules, and target. The only instruction was to "throw the ball as fast as you can to the net". Two valid measures were recorded, that is, an overarm throw such that the hand was approximately level with the shoulder joint and above the elbow throughout the throw. The throw with a faster ball release speed was analyzed.

2.3 | Selection of variables

For this study, a conceptual analysis model of segmental sequencing based on the "Kinetic Link Principle" was developed (Figure 1). This included the rotations and relative movements of the upper girdle (i.e., the upper thoracic and the scapulothoracic regions) and pelvic girdle, the three-dimensional shoulder joint movements, and the humeral rotation of the throwing arm. The shoulder joint movements of interest in the non-throwing side were extension, adduction, and depression, which were opposite to the throwing arm, based on the final stage of motor development of overarm throws.[34] For simplicity, only the flexion/extension of the elbow and wrist joint movements were considered. The arrows represent the theoretical sequences of joint contributions according to the "Kinetic Link Principle" based on the timing of achieving maximum joint angular velocity. For all segmental sequences in each group, the selected variables were (1) the times of maximum angular velocity of temporal events and (2) the times between two successive temporal events (i.e., temporal space between events).

2.4 | Kinematic data processing

All kinematic data of the right-handed throwers collected were processed using MATLAB (Version 9.4.0, The Mathworks, USA). The global coordinate frame was a "right-handed system" with the positive horizontal x-axis pointing in the direction of the throw toward the net. The positive y-axis was orthogonal to the x-axis on the transverse plane pointing to the left. The positive z-axis was a vertical perpendicular to the XY plane. The movement directions analyzed, and the choice of the temporal features (i.e., the time of maximum angular velocity of a segment or a joint), were based on the conceptual analysis model of a "proximal-distal" rotational sequencing of "right-handed" throwers (Figure 1). Raw 3D kinematic data were

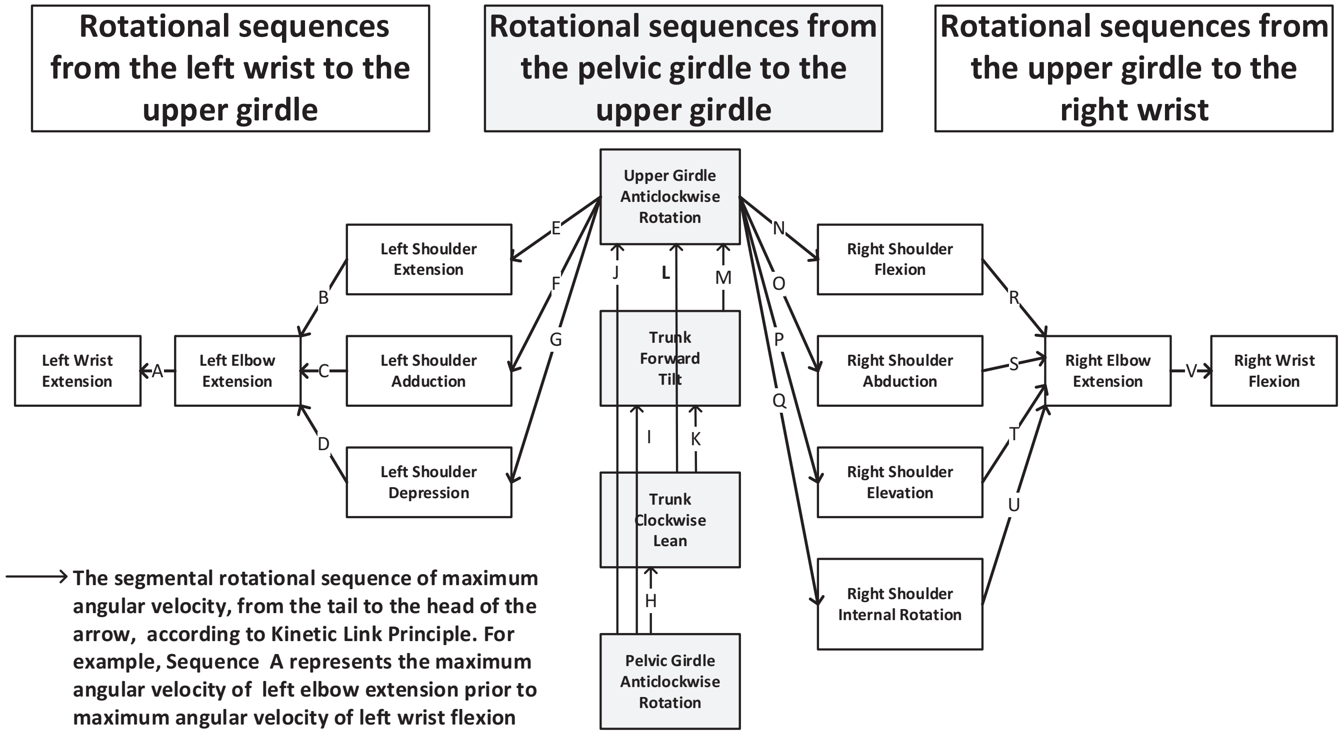

FIGURE 1 Conceptual analysis model of "proximal-distal" rotational sequencing in a right-handed thrower

filtered using a fourth-order Butterworth low pass digital filter with a cutoff frequency of 6 Hz. Given the goal of translating the findings into real-world practice,[35] we used Cardan angles and the mathematical models are detailed in Supplementary material S3. The shoulder and pelvic vector were formed by joining the center of the two shoulders and two hip joints, respectively (Supplementary material S2a). The trunk vector was formed by the midpoint of the center of the two shoulder joints and the center of the two hip joints. The upper and pelvic girdle rotation angles were defined as the angles formed between y-axis and the upper and pelvic girdle vector projection on the XY horizontal plane, respectively. The trunk lean angle was defined as the angle formed between the projection of the trunk vector on the YZ frontal plane and the z-axis, whereas the trunk tilt vector was defined as the angle formed between the projection of the trunk vector on XZ sagittal plane and the Z-axis.

The 3D shoulder joint angle calculation was based on the humeral vector orientation in relation to an orthogonal internal reference frame of the trunk using the "right-hand system" and Cardan angles except for rotations (Supplementary material S2b,c). The positive z-axis was defined as the trunk vector pointing upwards, and the positive y-axis was defined as the upper girdle vector pointing laterally in the corresponding arms. The positive x-axis was defined as a vector perpendicular to the yz frontal plane in the anterior direction. Shoulder flexion and extension were defined as the humeral vector moving away from the internal yz frontal plane anterior and posteriorly, abduction and adduction as the humeral vector moving away and toward the xz sagittal plane and elevation and depression as the humeral vector moving above and below the yx horizontal plane.

Right shoulder internal and external rotation was defined as another orthogonal internal reference frame using the "right-hand system" (Supplementary material S2d). The positive x-axis was the right humeral vector pointing toward the shoulder joint from the midpoint of the two epicondyles of the elbow. The z-axis of the internal reference frame was determined as the unit vector obtained from the cross product of the x-axis unit vector and the unit vector joining the epicondyles. The positive y-axis was obtained as the cross product of the x and y unit vectors. Shoulder internal and external rotation was obtained as a function of time as the cumulative sum from time zero to the instant of release (0.6 s) and referenced to the instant at which the X-coordinate of the center of the wrist joint was larger than the X-coordinate of the center of the shoulder joint by subtracting the cumulative value of internal rotation at that point in time.

The forearm vector was the segment formed between the elbow and wrist joints' centers, whereas the hand vector was the segment formed between the center of the wrist joint and the third metacarpal marker (Supplementary material S2d). Elbow and wrist joint angles were defined as the acute angle between the humerus and the forearm vector, and between the forearm and the hand vector, respectively. A fully flexed joint was expressed as 0°, and a fully extended elbow was expressed 180°.

The ball release time was defined as the first frame when the ball marker increased its linear displacement by 20 mm with respect to the third metacarpal marker.[4] The duration of one complete delivery was set as 0.60 s before the time of ball release as this was the absolute time of the fastest throw among all 144 participants.

2.5 | Statistical analysis

All statistical analyses were performed with IBM SPSS Statistics for Windows (Version 25.0. Armonk, NY, USA). The whole cohort was divided into four quartiles, each of 36 students, according to the maximum ball release speed normalized by the body height (NMaxBallv). This step minimized the effect of limb length as the tangential velocities of hand (and therefore the ball) are related to limb length. The quartile with the lowest and highest NMaxBallv were assigned as the Less Skilled Group and Skilled Group, respectively. Shapiro–Wilk statistic was used to check for normality. To compare participant characteristics between groups, the demographic (i.e., age and sex) and anthropometric data (i.e., height, weight, and BMI) were compared using independent *t*-tests, with the exception of sex for which a chi-square test was used to check for uneven distribution of males and females across quartiles. *p*-Values <0.05 were considered as significant for demographic analysis. The males and females were pooled for analysis as sex difference was not considered as a-priori to be a factor directly contributing to movement pattern variations at this age group. That is, boys and girls could both become equally skilled with equal practice. Further, there were no significant differences in anthropometric measures between sex in this study.

The times of maximum angular velocity of temporal events in Figure 1 for both groups were calculated as means±99%CI of the true mean. Paired t-test was used to determine the within-group differences between the times of attaining maximum angular velocity of two successive events. Independent t-tests were used to evaluate the between-group differences of temporal space between events for each sequence. To ensure the identified features are critical and of high significance, the α level was set as 0.001. Effects size was reported with Cohen's d for both paired and independent t-tests. A characteristic segmental sequencing of each group was defined as the sequence with significant within-group differences in two successive events; a critical segmental sequencing was defined as the sequence with significant within- and between-group differences. Finally, arrows were used to summarize the segmental sequencings of the Skilled and Less Skilled Group's successive segments in the conceptual analytical model.

3 | RESULTS

There was no significant difference in age, height, weight, and BMI ($p > 0.05$) but significantly more males ($n = 29$) than females ($n = 7$) in the Skilled than the Less Skilled Group ($\chi^2 = 16.37$, $p < 0.001$). There were 11 common segmental sequences (i.e., C - E, J, N, O, and Q - U), six segmental sequences in the Skilled Group only (i.e., A, B, F, G, P, and L), and two segmental sequences in the Less Skilled Group only (i.e., I and V) (Figure 2). Sequences H, K, and M did not exist in either group. Therefore, in total, the Skilled Group had 17 out of 22 segmental sequences and the Less Skilled Group had 13. Among these sequences, eight sequences followed the proximal-to-distal sequence (i.e., Sequences A, I, J, L, and Q–T) but 11 sequences (i.e., Sequences B to G, N to P, U, and V) did not follow. Further, the Skilled Group had significantly shorter temporal space between events than the Less Skilled Group in Sequences E and Q and longer for Sequences B and U. Therefore, the only one critical segmental sequencing was the sequence of maximum angular velocity of elbow extension to maximum angular velocity of shoulder clockwise rotation (Sequence B). The angular velocities of the upper limb and trunk rotations across time of a skilled throw and the critical segmental sequence are shown in Figure 3. The within-group comparison of the times of two successive events and the between-group comparison of temporal space are detailed in Supplementary Materials S4 and S5, respectively.

4 | DISCUSSIONS

The aim of this study was to identify the features of "skilled" and "less skilled" segmental sequence of joint and segment rotations of the upper body for maximum ball release speed in unconstrained overarm throws. Overall, the "skilled" adolescents had more segmental sequences and better throwing competency than the "less skilled." However, there is only one significant and critical segmental sequence. According to Roberton's stage model,[10] all early adolescents in this study performed at category III level while 83% of middle childhood were at category I and II and 2% at category III, implying the adolescents in this cohort should have improved skills compared to their middle childhood as expected. Regarding the trunk motion, both groups used the sequence of maximum angular velocity of pelvic girdle anticlockwise rotation prior to the maximum angular

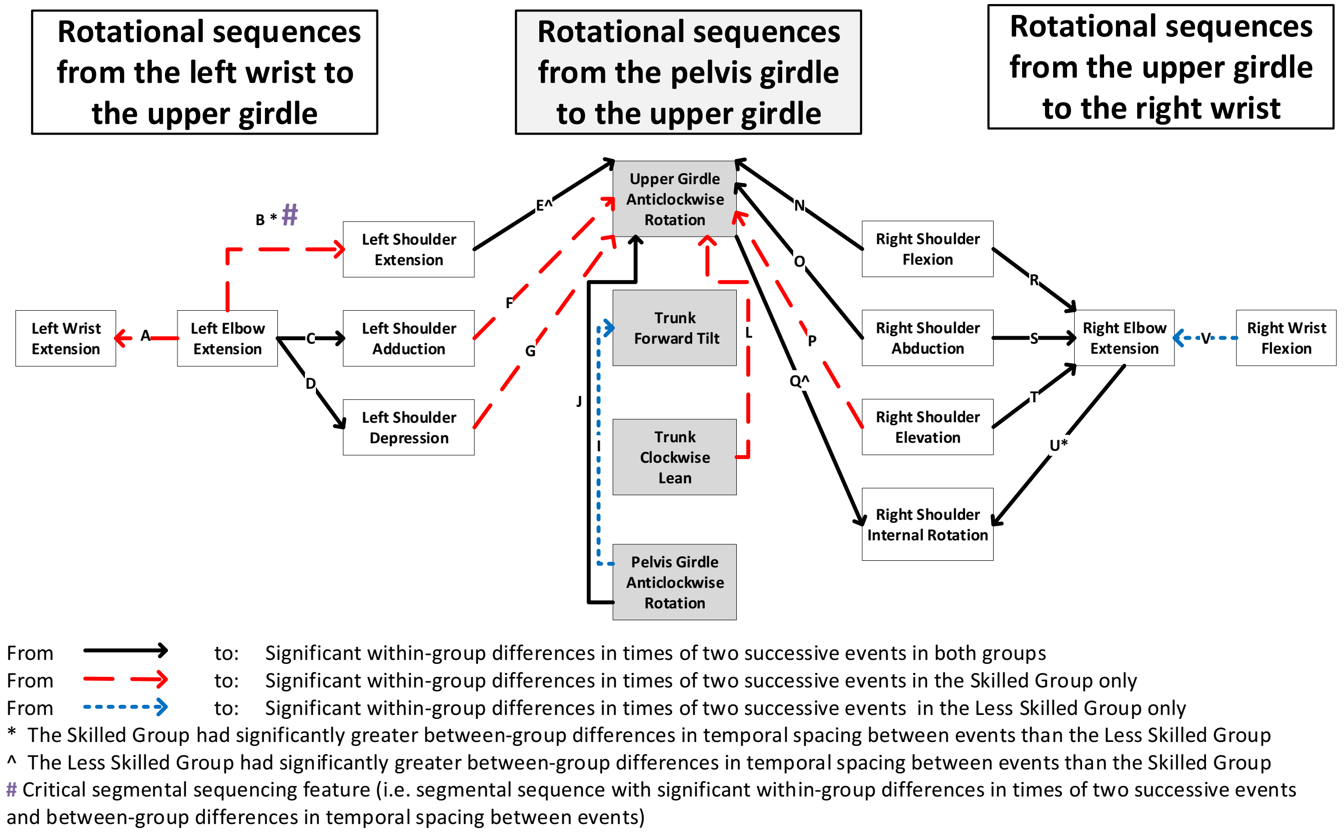

FIGURE 2 Rotational sequencing features of the Skilled and the Less Skilled Groups

velocity of the upper girdle rotation (Sequence J) which was in agreement with the existing throwing sports literature[6,8,18,22] but not previously identified as an FMS. However, the "skilled" used a segmental sequencing along the frontal plane. The maximum angular velocity of the trunk lean clockwise was followed by the maximum angular velocity of upper girdle anticlockwise rotation (Sequence L) due to a side-on approach. The "less skilled" applied a segmental sequence from the maximum angular velocity of the pelvic girdle anticlockwise rotation to the maximum angular velocity of the trunk forward tilt along the sagittal plane (Sequence I) due to the front-facing approach. As compared to the front-facing approach, the side-on approach "pre-stretched" the pelvis in a clockwise direction which facilitated the subsequent clockwise trunk lean and anticlockwise rotation of the upper girdle. This induced a greater transfer of angular momentum from the trunk to the throwing arm and then the ball via "proximal-to-distal" sequencing. It should be emphasized that Sequence J is a common sequencing, and the temporal gap between pelvic and upper girdle rotation was very small rather than being a distinct and observable pelvic rotation preceding the upper trunk rotation. Therefore, the instruction in which "Hip then shoulder rotates forward" in the coaching manuals[29,31] should be revised as "pelvic rotation leads the upper trunk rotation toward the non-throwing side using a side-on approach" (Instruction 1).

The total number and motion of segmental sequencings in the throwing arm between the two groups were similar, indicating the coordination of the throwing arm in adolescents aged around 13 years are fairly well developed. To further improve the coordination, the "less skilled" should maximize the angular velocity of the distal hand segment (Sequence V), partially explaining the lower ball release speed in this group. According to the description of Kreighbaum and Barthels,[24] the movement patterns of the "skilled" were considered as "throw-like" while the "less skilled" were "push-like." It is noted that the segmental sequencing of elbow extension prior to wrist flexion is not a FMS, which is in line with the coaching manual. This temporal sequencing is controversial in some sports-specific overarm throws. For example, the findings of Fradet et al. concurred with this segmental sequence[15] but not for van den Tillaar and Ettema who found a reversed pattern.[17] Moreover, the "less skilled" should increase the maximum angular velocity of shoulder flexion preceding the upper girdle anticlockwise rotation (Sequence P), which is a skilled characteristic. The sequence of maximum angular velocity of upper girdle rotation preceding right shoulder rotation (Sequence Q) and the sequence of maximum angular velocity of shoulder

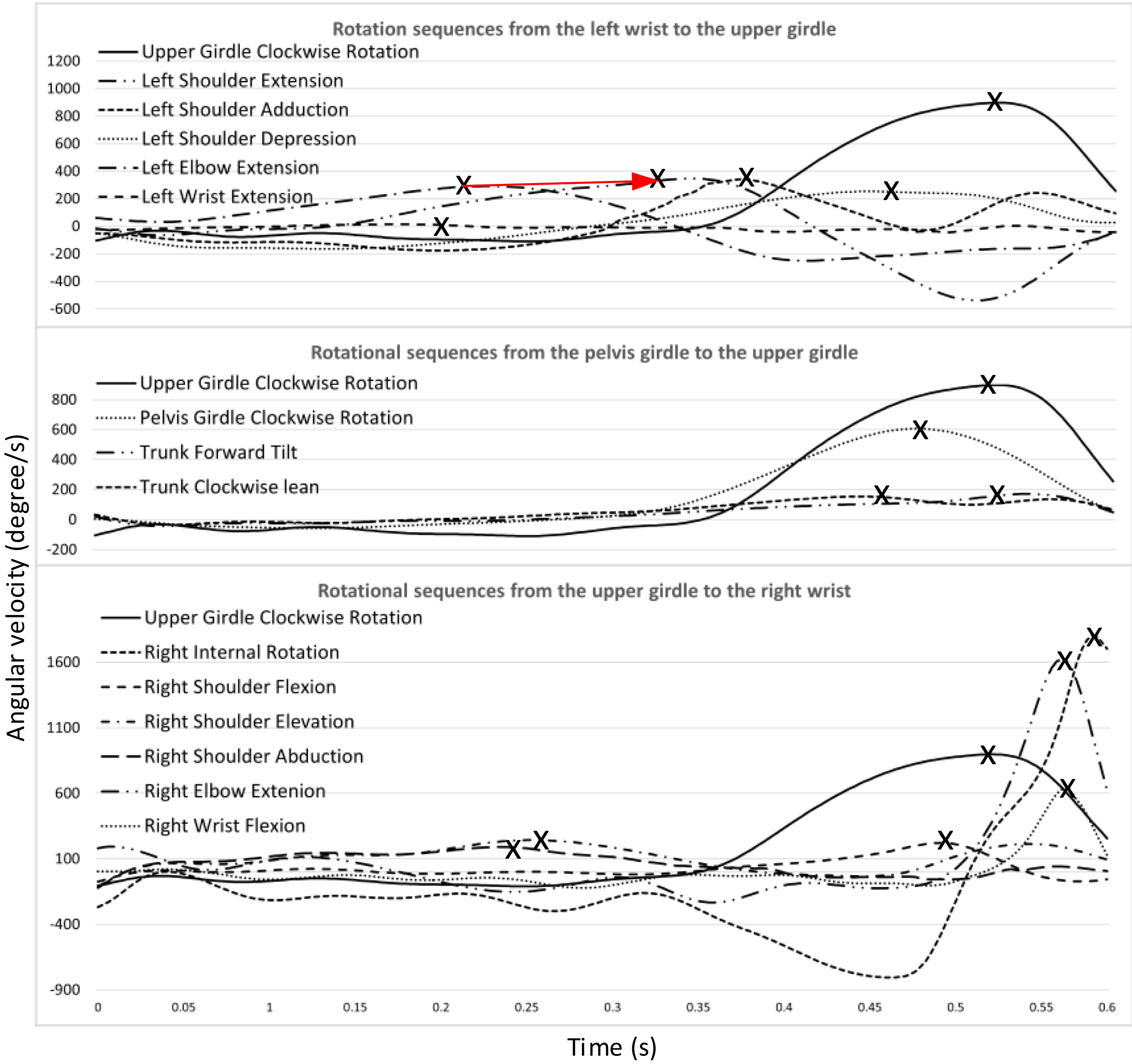

FIGURE 3 Angular velocity–time graphs of rotational sequences between the upper extremities of the Skilled Group. The x and ➔ symbols indicate the maximum angular velocity of the corresponding curves and the critical segmental sequence with significant between- and within-group time differences when compared to the Less Skilled Group

flexion/abduction/elevation preceding shoulder extension (Sequences R, S, and T) agreed with the sports-specific overarm throwing in proximal-to-distal sequencing,[6,18,22] implying that the adolescents can proceed to sport-specific training if the segmental sequencing in other body segments and joints are appropriately developed, which is irrespective to age.

However, it is also true that segmental sequences in the throwing arm disagree with the proximal-to-distal sequence since almost half of the segmental sequencing had a "distal-to-proximal sequence" in the throwing arm. This included the sequence of maximum angular velocity of right shoulder flexion/abduction/elevation preceding upper girdle anticlockwise rotation (Sequences N, O, and P), and the sequence of maximum angular velocity of right wrist flexion to right wrist extension and then to right shoulder internal rotation (Sequences U and V). For example, the segmental sequencing of right elbow extension prior to right shoulder internal rotation (Sequence U), which was in line with sports-specific studies,[6,26,36] but not previously identified as an FMS. Hong, Cheung, and Roberts[12] suggested that this sequence can reduce joint stress by decreasing the inertia and net torque around the shoulder rotation axis when the elbow is in an extended position. Further, by applying sequencings of right shoulder flexion/abduction/elevation prior to upper girdle anticlockwise rotation (Sequences N, O, and P), a cumulative increase in effective lever arm facilitated the upper girdle anticlockwise rotation by transferring the angular motion from the humerus to the upper girdle. Notably, there was no evidence that the shoulder flexed from an extended position (posterior to the trunk frontal plane) in this study. This contrasts with the findings of research in sports-related throws such as baseball,[37] handball,[17,28] and cricket.[7] This suggests that the prerequisites required to throw are dissimilar between FMS and sport-specific skills. Therefore, in the coaching manual, the throwers should be instructed to elevate the throwing arm while abducting and flexing (Instruction 2), to move the humerus forward before rotating the upper girdle toward the non-throwing side (Instruction 3), and to flex the throwing wrist while the elbow is extending (Instruction 4).

The "skilled" adolescents (i.e., Sequences A - G) had double the number of segmental sequencings in the non-throwing arm than the "less skilled" (i.e., Sequences C, D, and E) (Figure 2), signaling the non-throwing arm was more coordinated in the "skilled" than the "less skilled." The importance of the role of the non-throwing arm is further consolidated as the only critical feature was identified in the non-throwing arm with the segmental sequencing from elbow extension to shoulder extension (i.e., Sequence B). Despite this sequence lasting only ~0.159 s and being hard to observe, it appears to be necessary for initiating a powerful trunk rotation to lead the proximal-to-distal sequence of the throwing upper limbs to maximize ball release speed and should be correctly coached. However, this critical feature was neglected in the descriptions of skilled throwing in the extant literature and coaching manuals.[29,31,38] In the current manual, the non-throwing arm was advised to point toward the target for balancing. This instruction compromises the segmental sequencing between the joints in the non-throwing arm and the upper body, thus reducing throwing competence and partially explaining the decline of FMS performance despite the instructional interventions.[39] New instructions should emphasize the dynamic movements of the non-throwing arm in relation to the upper trunk clockwise rotation—"extend the elbow of the non-throwing arm and then draw the shoulder downwards, backwards and toward the trunk to facilitate upper trunk rotation toward the non-throwing side" (Instruction 5) (Table 1).

Another characteristic feature of the non-throwing arm was the "distal-to-proximal sequence," which is the prior attainment of maximum angular velocity of the distal smaller segment instead of the proximal larger segment. This included the sequence of maximum angular velocity of left elbow extension to left shoulder extension/adduction/depression and then to upper gridle anticlockwise rotation (Sequences B to G). The only exception was the maximum angular velocity of elbow extension to wrist extension (Sequence A). This finding is counter to that anticipated proximal-to-distal sequencing based on the "Kinetic Link Principle." It might be related to the triceps as the prime movers of the non-throwing arm actions, which are primarily responsible for elbow extension that transfer angular momentum from the forearm segment to the smaller hand segment. However, this hypothesis needs to be tested with the inclusion of EMG data. Given that the long head of triceps crosses both the shoulder and elbow joints, this facilitates the angular velocity of shoulder and elbow extension of the non-throwing arm. While extending the elbow does not directly increase the angular velocity of the larger upper girdle, it acts to transfer the motion and facilitates the upper girdle anticlockwise rotation.

The present study is the first to analyze segmental sequencings of the upper body for maximizing ball release speed in an unconstrained condition. The strength of this study was the holistic approach to analyzing the segmental sequencings using rigorous statistical analysis (i.e., $p < 0.001$) and adequate sample size. However, the contributions of the lower extremities were not considered in the analysis model, and is a present limitation. Another limitation was the use of 100 Hz measuring frequency, but

TABLE 1 Original skill criteria related to segmental sequencing for overarm throwing according to The Department of Education Western Australia instruction manual (2013) and recommended new criteria

Original skill instruction	Amended or new skill instruction in plain language
No prior mention	Extend the elbow of the non-throwing arm and then draw the shoulder downwards, backwards and toward the trunk
No prior mention	Elevate the throwing arm while abducting and flexing
No prior mention	Move the upper arm forward before rotating the upper girdle toward the non-throwing side
Hips then shoulders rotate forward	Pelvis rotation leads the upper trunk rotation toward the non-throwing side using a side-on approach
No prior mention	Flex the throwing wrist while the elbow is extending

this would not affect the movement analysis of gross body movement. Future studies may benefit from the investigating contribution of the lower limbs and how they relate to the upper body segmental sequencing. A previous study[40] demonstrated a significant effect of instructions on maximum ball velocity and maximal velocity of different body segments but not on the non-throwing arm, so the impact of instructions on performance and segmental sequencing deserves further investigation. The current and future studies will enable appropriate updates of the instructional content and design of interventions to improve throwing competency in the "less skilled" adolescents.

5 | PERSPECTIVES

Summarized in the conceptual model (Figure 2), the "skilled" overarm throwers had more segmental sequences than the "less skilled" throwers. Segmental-sequencing patterns between skill levels were similar in the throwing arm but different in the trunk and the non-throwing arm. Not all the segmental sequences are started from a proximal larger segment to distal smaller segment but also in reverse. The only critical segmental sequencing feature that distinguished the "skilled" and "less skilled" overarm throwers was the segmental sequence from elbow extension to shoulder extension of the non-throwing arm. This study added five evidence-based instructions on the existing coaching manual that impacted their lifelong throwing competency for sports and PA participation (Table 1).

ACKNOWLEDGEMENT

The Principal Roger Davis, Sports Director Alex Larkin and teachers from Westfields Sports High School, Australia.

FUNDING INFORMATION

Open access publishing facilitated by The University of Sydney, as part of the Wiley - The University of Sydney agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available on request due to privacy/ethical restrictions.

ORCID

Allan Chak Lun Fu https://orcid.org/0000-0002-9894-2367
Stephen Paul Cobley https://orcid.org/0000-0001-6099-392X
Ross Howard Sanders https://orcid.org/0000-0003-0489-3048

REFERENCES

1. Hulteen RM, Morgan PJ, Barnett LM, Stodden DF, Lubans DR. Development of foundational movement skills: a conceptual model for physical activity across the lifespan. *Sports Med*. 2018;48:1533-1540. doi:10.1007/s40279-018-0892-6
2. Department of Education Western Australia. Fundamental Movement Skills: Book 1 - Learning, Teaching and Assessment. 2013.
3. Fu ACL, Cobley SP, Sanders RH. Motor coordination training and pedagogical approach for combating childhood obesity. *Open J Soc Sci*. 2016;4:1-12. doi:10.4236/jss.2016.412001
4. Fu ACL. The Development of Throwing Competency to Break the Vicious Cycle of Inactivity and Obesity at the Critical Age [Doctor of Philosophy Ph.D.], Faculty of Health Sciences, University of Sydney; 2019.
5. Barnett LM, Stodden D, Cohen KE, et al. Fundamental movement skills: an important focus. *J Teach Phys Educ*. 2016;35(3):219-225. doi:10.1123/jtpe.2014-0209
6. Wagner H, Pfusterschmied J, Von Duvillard SP, Mueller E. Skill-dependent proximal-to-distal sequence in team-handball throwing. *J Sports Sci*. 2012;30(1):21-29. doi:10.1080/02640414.2011.617773
7. Beach AJ, Ferdinands RED, Sinclair PJ. The relationship between segmental kinematics and ball spin in Type-2 cricket spin bowling. *J Sports Sci*. 2018;36(10):1127-1134. doi:10.1080/02640414.2017.1358460
8. Oyama S, Yu B, Blackburn JT, Padua DA, Li L, Myers JB. Improper trunk rotation sequence is associated with increased maximal shoulder external rotation angle and shoulder joint force in high school baseball pitchers. *Am J Sports Med*. 2014;42(9):2089-2094. doi:10.1177/0363546514536871
9. Serrien B, Baeyens J-P. Systematic review and meta-analysis on proximal-to-distal sequencing in team handball: prospects for talent detection? *J Hum Kinet*. 2018;63:9-21. doi:10.2478/hukin-2018-0002
10. Roberton MA. *Stability of Stage Categorizations across Trials: Implications for the" Stage Theory" of Overarm Throw Development*. The University of Wisconsin-Madison; 1975.
11. Cattuzzo MT, Dos Santos HR, Ré AH, et al. Motor competence and health related physical fitness in youth: a systematic review. *J Sci Med Sport Sports Med Austr*. 2016;19(2):123-129. doi:10.1016/j.jsams.2014.12.004
12. Hong D-A, Cheung TK, Roberts EM. A three-dimensional, six-segment chain analysis of forceful overarm throwing. *J Electromyogr Kinesiol*. 2001;11(2):95-112. doi:10.1016/S1050-6411(00)00045-6
13. Hirashima M, Kadota H, Sakurai S, Kudo K, Ohtsuki T. Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *J Sports Sci*. 2002;20(4):301-310. doi:10.1080/026404102753576071
14. Marshall RN. Proximal-to-distal Sequencing Research: Application to Throwing. *Int Res Sports Biomech*. 2002;9:949-955.
15. Fradet L, Botcazou M, Durocher C, et al. Do handball throws always exhibit a proximal-to-distal segmental sequence? *J Sports Sci*. 2004;22(5):439-447. doi:10.1080/02640410310001641647

16. Hirashima M, Yamane K, Nakamura Y, Ohtsuki T. Kinetic chain of overarm throwing in terms of joint rotations revealed by induced acceleration analysis. *J Biomech*. 2008;41(13):2874-2883. doi:10.1016/j.jbiomech.2008.06.014
17. van den Tillaar R, Ettema G. Is there a proximal-to-distal sequence in overarm throwing in team handball? *J Sports Sci*. 2009;27(9):949-955. doi:10.1080/02640410902960502
18. Wagner H, Pfusterschmied J, Tilp M, Landlinger J, von Duvillard SP, Müller E. Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike: kinematic differences in overarm movements. *Scand J Med Sci Sports*. 2014;24(2):345-354. doi:10.1111/j.1600-0838.2012.01503.x
19. Putnam CA. Sequential motions of body segments in striking and throwing skills: descriptions and explanations. *J Biomech*. 1993;26(Supplement 1):125-135. doi:10.1016/0021-9290(93)90084-R
20. van der Graaff E, Hoozemans M, Nijhof M, Davidson M, Hoezen M, Veeger D. The role of pelvis and thorax rotation velocity in baseball pitching. Paper presented at: ISBS-Conference Proceedings Archive2016.
21. Serrien B, Baeyens J-P. The proximal-to-distal sequence in upper-limb motions on multiple levels and time scales. *Hum Mov Sci*. 2017;55:156-171. doi:10.1016/j.humov.2017.08.009
22. van den Tillaar R, Zondag A, Cabri J. Comparing performance and kinematics of throwing with a circular and whip-like wind up by experienced handball players. *Scand J Med Sci Sports*. 2013;23(6):e373-e380. doi:10.1111/sms.12091
23. Bunn JW. *Scientific Principles of Coaching*. Prentice Hall; 1972.
24. Kreighbaum E, Barthels KM. *Biomechanics: A Qualitative Approach for Studying Human Movement*. Allyn and Bacon; 1996.
25. Kageyama M, Sugiyama T, Takai Y, Kanehisa H, Maeda A. Kinematic and kinetic profiles of trunk and lower limbs during baseball pitching in collegiate pitchers. *J Sports Sci Med*. 2014;13(4):742.
26. Reid M, Giblin G, Whiteside D. A kinematic comparison of the overhand throw and tennis serve in tennis players: how similar are they really? *J Sports Sci*. 2015;33(7):713-723. doi:10.1080/02640414.2014.962572
27. Murata A. Shoulder joint movement of the non-throwing arm during baseball pitch—comparison between skilled and unskilled pitchers. *J Biomech*. 2001;34(12):1643-1647. doi:10.1016/S0021-9290(01)00154-3
28. van den Tillaar R, Ettema G. A comparison of overarm throwing with the dominant and nondominant arm in experienced team handball players. *Percept Mot Skills*. 2009;109(1):315-326. doi:10.2466/pms.109.1.315-326
29. Department of Education Western Australia. *Fundamental Movement Skills: Book 2 - the Tools for Learning, teaching and assessment*. 2013.
30. Government of Western Australia. Physical Education Fundamental Movement Skills Performance Assessment Supoort Material Overarm Throw. Australia 2017.
31. Department of Education Australia. Fundamental Motor Skills: A Manual for Classroom Teachers. Vol 2015. Victoria: Melbourne1996.
32. Gallahue DL, Ozmun JC, Goodway J. *Understanding motor development: infants, children, adolescents, adults*. McGraw-Hill; 2012.
33. Wall AET. The developmental skill-learning gap hypothesis: implications for children with movement difficulties. *Adapt Phys Activ Q*. 2004;21(3):198-218. doi:10.1123/apaq.21.3.197
34. Seefeldt V, Haubenstricker J. Patterns, phases, or stages: An analytical model for the study of developmental movement. *Development of Movement Control and Coordination*. John Wiley & Sons; 1982:309-318.
35. Tupling SJ, Pierrynowski MR. Use of cardan angles to locate rigid bodies in three-dimensional space. *Med Biol Engineer Comp*. 1987;25(5):527-532. doi:10.1007/BF02441745
36. Serrien B, Clijsen R, Blondeel J, Goossens M, Baeyens J-P. Differences in ball speed and three-dimensional kinematics between male and female handball players during a standing throw with run-up. *BMC Sports Sci Med Rehabil*. 2015;7:27. doi:10.1186/s13102-015-0021-x. eCollection 2015.
37. Fleisig CS, Escamilla RF, Andrews JR, Matsuo T, Barrentine SW. Kinematic and kinetic comparison between baseball pitching and football passing. *J Appl Biomech*. 1996;12(2):207-224. doi:10.1123/jab.12.2.207
38. Fu ACL, Sanders RH. The effectiveness of coaching the Australian recommended fundamental overarm throwing skill criteria for less-skilled adolescents. *Res Q Exerc Sport*. 2022;1-9. doi:10.1080/02701367.2022.2070120. Online ahead of print.
39. Hardy LL, Barnett L, Espinel P, Okely AD. Thirteen-year trends in child and adolescent fundamental movement skills: 1997-2010. *Med Sci Sports Exerc*. 2013;45(10):1965-1970. doi:10.1249/MSS.0b013e318295a9fc
40. van den Tillaar R, Ettema G. A comparison between novices and experts of the velocity-accuracy trade-off in overarm throwing. *Percept Mot Skills*. 2006;103(2):503-514. doi:10.2466/pms.103.2.503-514

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Fu ACL, Cobley SP, Sanders RH. Segmental sequencing of the upper body segments in unconstrained maximum overarm throws: An implication for coaching. *Scand J Med Sci Sports*. 2022;32:1747-1756. doi: 10.1111/sms.14233