

Kinematic Assessment Capability of Single- and Dual-IMU Configurations During Squats and Deadlifts

Samson Nanxin Zhang

`nxzhang3@connect.hku.hk`

University of Hong Kong

Article

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Abstract

Background

This study evaluated the kinematic assessment capability of a low-complexity system, defined as one or two body-worn inertial measurement units (IMUs) using segment-level measures, during front squats, deadlifts, and back squats.

Methods

Forty-six adults completed 10 repetitions of each exercise under standardized submaximal loading and cadence-controlled conditions. IMUs were placed on the upper back and left thigh. Exercise effects were evaluated across 48 measures with false-discovery-rate control. Elastic-net multinomial regression with leave-one-participant-out validation compared upper-back-only, thigh-only, and combined configurations.

Results

Twelve kinematic measures differed among exercises. Seven were upper-back-derived: sagittal excursion; mean, 95th-percentile, and maximum recorded sagittal angular speed; sagittal velocity-profile ratio; and mean frontal- and transverse-plane angular speed. Three were thigh-derived: mean sagittal and transverse angular speed and sagittal velocity-profile ratio. Paired sagittal measures, normalized trunk-thigh excursion difference and trajectory correlation, were significant. No timing or repetition-consistency measure remained significant. Balanced accuracy was 65.2% for upper-back only, 42.8% for thigh only, and 63.0% for the combined configuration. Adding thigh-derived and paired measures did not improve performance over upper-back only in unseen participants.

Conclusions

Among the tested configurations, a single upper-back IMU provided the strongest exercise-specific assessment capability. The dual-IMU configuration added trunk-thigh information without improving exercise discrimination.

1 INTRODUCTION

Squats and deadlifts are widely used in fitness, sports performance, and rehabilitation. Their movement characteristics vary with bar position, trunk and tibial orientation, stance, depth, and the relative contributions of the trunk and lower limbs [1–5]. These differences can be characterized using segmental excursion, angular speed, repetition timing, and repetition-to-repetition consistency. Optical motion capture enables detailed biomechanical assessment but has limited routine field use because of its equipment, calibration, technical, and marker-visibility requirements [6]. Wearable inertial measurement units (IMUs) provide a more portable alternative for assessing movement outside laboratory settings.

IMUs have been used to quantify segmental kinematics, movement velocity, repetition timing, and movement variability, as well as to identify resistance exercises [7–15]. However, assessment performance depends on sensor placement, the number of sensors, feature selection, modelling approach, and validation design [16]. Reducing system complexity may improve portability and usability, but it also limits the segments and intersegmental relationships that can be observed. Low effective recording rates may further restrict the representation of rapid movement changes and recorded speed extrema [17, 18].

For this study, low complexity was defined as using one or two body-worn IMUs with interpretable segment-level measures that did not require anatomical joint modelling. Previous research has demonstrated IMU-based assessment

and classification of resistance exercises, but limited evidence directly compares the information captured by upper-back, thigh, and combined upper-back-thigh configurations under the same exercise conditions. In particular, it remains unclear whether a second IMU provides meaningful information beyond that available from a single appropriately positioned sensor.

This study therefore compared the kinematic assessment capability of upper-back-only, thigh-only, and combined upper-back-thigh configurations during slow, cadence-controlled, low-load front squats, deadlifts, and back squats. The primary objectives were to determine which prespecified kinematic, timing, and repetition-consistency measures differed among exercises and to compare the ability of the three configurations to distinguish exercises in previously unseen participants. The incremental value of the combined configuration over each single-IMU configuration was also evaluated. It was hypothesized that upper-back measures would show greater exercise-specific sensitivity and discrimination than thigh measures. The combined configuration was expected to provide additional intersegmental information, although whether this information would improve participant-independent exercise discrimination was considered uncertain. As a secondary exploratory objective, associations with knee-extension strength and differences between women and men were examined to assess whether the extracted measures captured participant-related variation.

2 METHODS

2.1 Study Design

A cross-sectional repeated-measures design was used to compare the kinematic assessment capability of single- and dual-IMU configurations during front squats, deadlifts, and back squats. Each participant completed all three exercises under standardized submaximal loading and cadence conditions. Motion of the upper back and left thigh was recorded using two wearable IMUs. The data were evaluated as three configurations: upper-back only, thigh only, and combined upper-back-thigh.

Assessment capability was evaluated at two levels. First, feature-level analyses identified kinematic, timing, and repetition-consistency measures that differed among exercises. Second, participant-independent classification assessed whether each configuration distinguished the exercises in previously unseen participants and whether the combined configuration provided additional discriminative information beyond either single-IMU configuration. Associations with knee-extension strength and differences between women and men were examined as secondary exploratory analyses.

2.2 Participants and Experimental Procedures

Participants

Forty-six healthy, recreationally active adults participated, including 22 women and 24 men. Their mean age was 28.2 years (SD 10.3). Participants were recruited from university and local fitness communities.

Eligibility criteria included previous familiarity with the three exercises, independence in activities of daily living, and the ability to perform sit-to-stand and trunk-bending movements. Participants were excluded if they reported back or lower-extremity pain or injury within the preceding six months, or any medical condition contraindicating resistance exercise.

All participants provided written informed consent before testing. The study was approved by the Human Research Ethics Committee of The University of Hong Kong (reference EA240113).

Testing Session and Familiarization

Each participant completed one testing session comprising a dynamic warm-up, exercise familiarization, maximal isometric knee-extension strength testing, IMU placement and calibration, and three exercise trials.

A trained research assistant demonstrated the front squat, deadlift, and back squat, explained the required movement pattern and cadence, and supervised practice repetitions. Testing commenced after the participant demonstrated safe and consistent execution of each exercise.

Maximal Isometric Knee Extension Strength Testing

Maximal isometric knee-extension force was assessed bilaterally using a handheld dynamometer (Commander Echo Manual Muscle Tester, JTech Medical, USA). Participants were seated with the tested thigh supported and the lower leg hanging freely without heel contact. The dynamometer was positioned against the anterior lower leg approximately 5 cm proximal to the lateral malleolus.

Participants completed two maximal 3-s efforts with each leg, with standardized verbal encouragement and 30 s of rest between efforts. The highest recorded value for each leg was retained, and the two values were summed to represent total bilateral knee-extension force. This measure was analyzed as a continuous variable separately in women and men.

IMU Placement, Calibration, and Data Acquisition

IMU data were acquired using an in-house wearable system previously developed by the author [19]. Two IMUs (WT901C485, WitMotion, China) were calibrated on a horizontal surface and secured between the first and second thoracic vertebrae and over the anterior left thigh. Their axes were aligned approximately with the anatomical planes, with flexion-extension represented primarily by rotation about the X-axis. Elastic straps were used to minimize sensor movement relative to the body segments. Sensor placement and orientation are shown in Fig. 1.

The IMUs provided device-computed three-axis orientation and angular-velocity outputs. Data were acquired through sequential RS485 polling, with the upper-back IMU queried before the thigh IMU during each cycle. The two sensors were therefore recorded sequentially rather than simultaneously. The median interval between consecutive records from the same sensor was 0.535 s, corresponding to an effective recording rate of approximately 1.87 Hz per sensor. Paired records were matched by polling-cycle order within each continuous recording segment. Sagittal-plane motion was designated as the primary outcome.

Exercise Protocol

Participants performed the front squat, deadlift, and back squat in a fixed sequence under researcher supervision. An adjustable barbell system (YiTeng, China) was used, with standardized absolute loads of 10 kg for men and 2.5 kg for women.

Each exercise comprised 10 continuous repetitions paced by a metronome at 60 beats·min⁻¹. A four-count rhythm produced a target duration of approximately 4 s per repetition. For the squat exercises, counts 1 and 2 represented the downward phase and counts 3 and 4 represented the upward phase. For the deadlift, counts 1 and 2 represented the upward phase and counts 3 and 4 represented the downward phase.

Participants rested for at least 30 s between exercises, with additional rest provided when required. IMU and video data were recorded throughout the three exercise trials.

2.3 IMU Data Processing, Feature Selection and Extraction

Quality Control and Pre-processing

Timestamped sensor records were screened for invalid device identifiers, incorrect acquisition order, non-monotonic timestamps, missing or non-numeric values, all-zero frames, sensor-range violations, duplicated responses, long acquisition gaps, and local signal discontinuities. The median interval between consecutive records was used to characterize the effective recording interval, and timing variability was estimated using the scaled median absolute deviation [20]. Long gaps defined separate continuous recording segments. Timing-dependent and paired-sensor measures were not calculated across segment boundaries. Technically invalid records and records with unresolved device identity were excluded. No missing record met the prespecified criteria for interpolation. All analyses therefore used measured observations without smoothing, interpolation, or fixed-rate resampling.

Exercise-Set and Repetition Segmentation

Exercise sets and repetitions were identified using a video-assisted, human-in-the-loop procedure. Full-session video and IMU trajectories were first reviewed to identify approximate ranges for the front squat, deadlift, and back squat sets. These annotations localized each exercise but did not define the final analytical boundaries.

Within each localized set, orientation signals were robustly standardized and combined using principal-component analysis to generate a movement-cycle signal. An activity signal derived from angle-change rates and three-axis angular-speed magnitude was used to identify sustained movement. Candidate repetition boundaries were identified from recurring low-speed turning points and local extrema [21–23].

Duration-constrained dynamic programming selected an ordered sequence of repetition boundaries using signal evidence and the prescribed 4-s cadence as a soft temporal prior. All automatically identified boundaries were subsequently reviewed against the video and IMU trajectories. Preparation, barbell handling, postural adjustments, movement disturbances, and incomplete repetitions were excluded. Only complete, manually verified repetitions were retained for feature extraction.

Feature Selection and Extraction

Features were selected to evaluate which movement characteristics could be assessed using the upper-back IMU, thigh IMU, or their combination. Selection prioritized biomechanical relevance, interpretability, and suitability for the system's low effective recording rate. Whole-repetition summaries were preferred over measures requiring precise phase transitions, time lags, higher-order derivatives, or continuous-time velocity peaks [17].

The prespecified measures quantified segmental angular excursion, recorded angular speed, repetition timing, within-set consistency, and paired trunk-thigh movement relationships (Table 1). Timing measures comprised repetition duration, signed cadence error, and absolute cadence deviation. Recorded-speed extrema were considered secondary because of their sensitivity to temporal resolution [17]. Within-set consistency measures were calculated when at least three valid repetitions were available [11].

Segment-specific measures were calculated separately for the upper back and thigh in the sagittal, frontal, and transverse planes. Sagittal-plane measures were designated as primary. Frontal- and transverse-plane measures were considered secondary and exploratory, respectively, because their interpretation may be more sensitive to sensor placement and orientation [24]. Paired sagittal-plane measures comprised normalized trunk-thigh excursion difference and trajectory correlation.

Features were calculated for each verified repetition and summarized using the median across repetitions within each exercise. Trajectory correlations were averaged after Fisher z transformation. The resulting dataset contained 144 exercise-specific variables derived from 48 prespecified measures across the three exercises. A complete variable list is provided in **Supplementary Table S1**.

Table 1
Prespecified IMU Measures

Feature Type	Domain	Feature(s)	Formula	Meaning
Kinematic	Angular excursion [24]	RAE	$P95(\theta) - P5(\theta)$	Robust segment angular excursion within one repetition.
Kinematic	Average angular speed [17]	MAV	$\text{mean}(\omega)$	Average recorded angular speed over one repetition.
Kinematic	Relative segment excursion [25]	NED	$\frac{RAE_{\text{TRUNK}} - RAE_{\text{THIGH}}}{RAE_{\text{TRUNK}} + RAE_{\text{THIGH}} + e}$ <i>*e = 10⁻⁹ prevents division by zero</i>	Relative trunk-versus-thigh excursion magnitude.
Kinematic	Trajectory co-variation [25, 26]	TRAJ_R	$\text{corr}(\theta_{\text{TRUNK}}, \theta_{\text{THIGH}})$	Linear similarity of paired trunk and thigh orientation trajectories.
Kinematic	Recorded-speed descriptors [17]	P95AV; MRAV; VPR	$P95AV = P95(\omega);$ $MRAV = \max(\omega);$ $VPR = \frac{MAV}{P95AV}$	Upper recorded angular speed; maximum recorded angular speed; relative speed-profile level.
Timing	Repetition timing and cadence [27]	DUR; CE; ACD	$DUR = t_{\text{end}} - t_{\text{start}};$ $CE = DUR - T_{\text{target}};$ $ACD = DUR - T_{\text{target}} $	Elapsed repetition time; signed cadence error; absolute cadence deviation.
Consistency	Within-set consistency [11]	CV_RAE; CV_MAV; CV_DUR	$CVx = 100 \times \frac{SD(X)}{\text{mean}(X)}$ <i>*X is RAE, MAV, or DUR</i>	Conventional repetition-to-repetition variability in excursion, average speed, or duration.
Consistency	Robust within-set consistency [11]	RCV_RAE; RCV_MAV	$RCVx = 100 \times 1.4826 \times \frac{MAD(X)}{\text{median}(X)}$ <i>*X is RAE or MAV</i>	Outlier-resistant repetition-to-repetition variability.
Note: Abbreviations: ACD, absolute cadence deviation; CE, signed cadence error; CV, coefficient of variation; DUR, repetition duration; MAD, median absolute deviation; MAV, mean absolute angular velocity; MRAV, maximum recorded absolute angular velocity; NED, normalized excursion difference; P95AV, 95th-percentile recorded absolute angular velocity; RAE, robust angular excursion; RCV, robust coefficient of variation; TRAJ_R, trunk-thigh trajectory correlation; VPR, velocity-profile ratio.				

2.4 Statistical Analysis

Analysis Framework

Continuous variables were summarized using mean and standard deviation or median and interquartile range, as appropriate. The primary analyses comprised feature-level comparisons among exercises and participant-independent exercise classification. Associations with knee-extension strength and differences between women and men were examined as secondary exploratory analyses.

Exercise-Specific Differences

Exercise effects were evaluated for each of the 48 prespecified measures using Friedman tests, including participants with valid data for all three exercises. Benjamini-Hochberg false-discovery-rate adjustment was applied across the 48 omnibus tests, with adjusted values reported as q values.

Measures with a significant omnibus effect were examined using Wilcoxon signed-rank tests for front squat versus deadlift, front squat versus back squat, and deadlift versus back squat. The three pairwise comparisons within each measure were adjusted using the Holm method. Kendall's W and matched-pairs rank-biserial correlation were reported as omnibus and pairwise effect sizes, respectively, with participant-level bootstrap 95% confidence intervals.

Findings were summarized according to sensor source: upper-back-derived, thigh-derived, paired trunk-thigh, and common timing measures. Significant paired trunk-thigh measures were interpreted as additional descriptive intersegmental information provided by the dual-IMU configuration, rather than evidence of improved predictive performance.

Exercise Discrimination in Unseen Participants

Participant-independent exercise discrimination was evaluated for the upper-back-only, thigh-only, and combined upper-back-thigh configurations. Each single-IMU configuration included measures derived from the corresponding sensor and the common timing measures. The combined configuration included measures from both sensors and the paired trunk-thigh measures.

Elastic-net-regularized multinomial logistic regression was used to classify front squats, deadlifts, and back squats [28, 29]. Leave-one-participant-out validation was applied, with all three exercise records from one participant withheld during each outer iteration. Model hyperparameters were selected within the remaining participants using five-fold participant-grouped cross-validation, ensuring that all records from a participant remained in the same fold. The resulting model was then applied to the withheld participant.

Predictions from all withheld participants were pooled to calculate balanced accuracy, macro-F1, and class-specific recall. Balanced accuracy was defined as the unweighted mean of class-specific recall, and macro-F1 as the unweighted mean of class-specific F1 scores.

Performance differences between configurations were estimated using paired participant-level bootstrap resampling. Participants were sampled with replacement, all three predictions from each sampled participant were retained, and identical bootstrap samples were applied to each configuration. Incremental performance was defined as the combined-configuration metric minus the corresponding single-IMU metric. A 95% confidence interval excluding zero in the positive direction was interpreted as evidence that the combined configuration improved exercise discrimination.

Exploratory Participant-Related Information

Associations between total knee-extension force and exercise-specific IMU measures were examined separately in women and men using linear regression with standardized variables and HC3-robust 95% confidence intervals. Spearman correlations were used as sensitivity analyses.

Differences between women and men were evaluated using Welch independent-samples t tests and quantified using Hedges' g, signed as women minus men, with 95% confidence intervals. Strictly positive, right-skewed variables were log-transformed when appropriate, and Mann-Whitney U tests were used as sensitivity analyses.

Benjamini-Hochberg false-discovery-rate adjustment was applied separately to the primary strength analyses in women, primary strength analyses in men, and comparisons between women and men. Sensitivity analyses were adjusted separately. All participant-related findings were considered exploratory.

3 RESULTS

3.1 Participant Characteristics

All 46 participants provided sufficient valid data for the three exercises. The sample included 22 women and 24 men, with a mean age of 28.2 years (SD 10.3). Mean total bilateral knee-extension force was 51.8 kg (SD 12.8) (Table 2).

Table 2 Participant Characteristics		
Characteristic	Mean (SD) or n	Median [IQR] or %
Participants, n	46	
Women, n (%)	22	47.8%
Men, n (%)	24	52.2%
Age, years	28.2 (10.3)	25.0 [22.0, 28.8]
Left knee-extension force, kg	26.4 (6.1)	26.3 [22.0, 30.3]
Right knee-extension force, kg	25.4 (7.1)	26.1 [19.0, 30.8]
Total knee-extension force, kg	51.8 (12.8)	52.0 [40.2, 60.8]

3.2 Exercise-Specific Differences

After false-discovery-rate adjustment across the 48 omnibus Friedman tests, 12 measures showed significant differences among exercises. All 12 were kinematic measures. No timing or repetition-consistency measure remained significant after adjustment.

Seven of the nine upper-back kinematic measures showed exercise effects, compared with three of the nine thigh kinematic measures. Both paired trunk-thigh measures were also significant (Fig. 2).

- **Upper-back measures:** sagittal angular excursion; mean, 95th-percentile, and maximum recorded sagittal angular speed; sagittal velocity-profile ratio; and mean frontal- and transverse-plane angular speed. Kendall’s W ranged from 0.16 to 0.71.
- **Thigh measures:** mean sagittal and transverse angular speed and sagittal velocity-profile ratio. Kendall’s W ranged from 0.13 to 0.21.
- **Paired trunk-thigh measures:** normalized sagittal excursion difference and sagittal trajectory correlation. Kendall’s W ranged from 0.23 to 0.69.

Exercise effects were therefore more prevalent among upper-back kinematic measures than among thigh kinematic measures. The significant paired measures provided additional descriptive information about relative trunk-thigh excursion and trajectory similarity.

Among the 36 pairwise comparisons arising from the 12 significant omnibus tests, 30 remained significant after Holm adjustment. These comprised nine front-squat versus back-squat comparisons, 11 front-squat versus deadlift

comparisons, and 10 back-squat versus deadlift comparisons. Complete omnibus and pairwise results, including nonsignificant findings, are provided in **Supplementary Table S2**.

3.3 Exercise-Discrimination Performance in Unseen Participants

All 46 participants contributed one front-squat, one deadlift, and one back-squat record to the leave-one-participant-out evaluation, yielding 138 out-of-sample predictions for each configuration.

The upper-back-only and thigh-only models each included 25 candidate measures: nine sensor-specific kinematic measures, 12 sensor-specific repetition-consistency measures, and four common timing-related measures. The combined model included all 48 candidate measures: 20 kinematic, three timing, and 25 repetition-consistency measures, including the two paired trunk-thigh measures.

The upper-back-only configuration achieved the highest balanced accuracy at 65.2%, followed by the combined configuration at 63.0% and the thigh-only configuration at 42.8% (Table 3). Macro-F1 scores showed the same pattern.

Deadlifts were identified most accurately by the upper-back-only and combined configurations, with recalls of 82.6% and 89.1%, respectively. Front squats and back squats were more frequently confused. The thigh-only configuration showed similar and relatively low recall across all three exercises.

Table 3
Out-of-sample exercise-classification performance by sensor configuration

Configuration	n predictions	Balanced accuracy	Macro-F1	FS recall	BS recall	DL recall
Upper-back only	138	65.2% (60.1%-70.3%)	65.1% (59.2%-70.3%)	63.0% (50.0%-76.1%)	50.0% (34.8%-63.0%)	82.6% (71.7%-93.5%)
Thigh only	138	42.8% (37.0%-48.6%)	42.8% (36.5%-48.4%)	41.3% (28.3%-54.4%)	45.7% (32.6%-60.9%)	41.3% (28.3%-54.3%)
Combined upper-back-thigh	138	63.0% (57.2%-68.8%)	62.7% (56.4%-68.6%)	52.2% (37.0%-65.2%)	47.8% (34.7%-63.0%)	89.1% (80.4%-97.8%)
Note: Values are estimates with paired participant-level bootstrap 95% confidence intervals. Balanced accuracy is the unweighted mean of class-specific recalls. Macro-F1 is the unweighted mean of class-specific F1 scores. The 33.3% reference applies to balanced accuracy under uniform random guessing, not to macro-F1. The four common timing-related features comprise DUR, CE, ACD, and CV_DUR. FS, front squat; BS, back squat; DL, deadlift.						

Relative to the upper-back-only configuration, the combined configuration did not improve balanced accuracy, with a difference of – 2.2 percentage points (95% CI – 8.0 to 3.6), or macro-F1, with a difference of – 2.4 percentage points (95% CI – 8.8 to 4.0). Relative to the thigh-only configuration, the combined configuration improved balanced accuracy by 20.3 percentage points (95% CI 13.0 to 28.3) and macro-F1 by 19.9 percentage points (95% CI 11.9 to 28.0) (Fig. 3).

Thus, adding upper-back measures to the thigh-based configuration improved exercise discrimination, whereas adding thigh-derived and paired trunk-thigh measures to the upper-back-based configuration provided no improvement in overall classification performance.

3.4 Exploratory Participant-Related Findings

No association between total knee-extension force and the exercise-specific IMU measures remained significant after sex-specific false-discovery-rate adjustment. Spearman sensitivity analyses produced the same conclusion.

Four measures differed between women and men after FDR adjustment of the primary Welch tests. All were thigh sagittal-plane kinematic measures recorded during the back squat. Women showed lower:

- mean recorded angular speed, Hedges' $g = -1.22$ (95% CI -1.85 to -0.59 ; $q = 0.016$);
- angular excursion, $g = -0.99$ (95% CI -1.60 to -0.37 ; $q = 0.049$);
- 95th-percentile recorded angular speed, $g = -1.02$ (95% CI -1.64 to -0.41 ; $q = 0.049$); and
- maximum recorded angular speed, $g = -0.99$ (95% CI -1.61 to -0.38 ; $q = 0.049$).

No upper-back, paired trunk-thigh, timing, or repetition-consistency measure differed significantly between women and men after FDR adjustment. No front-squat or deadlift measure remained significant.

The corresponding Mann-Whitney sensitivity analyses showed the same direction of difference but did not remain significant after separate FDR adjustment, with q values ranging from 0.074 to 0.129. These findings were therefore sensitive to the statistical method and were considered exploratory. Full participant-related results are provided in **Supplementary Table S3**.

4 DISCUSSION

4.1 Principal Findings

This study compared the kinematic assessment capability of upper-back-only, thigh-only, and combined upper-back-thigh IMU configurations during front squats, deadlifts, and back squats. The principal finding was that the upper-back-only configuration provided the strongest exercise-specific assessment capability. Upper-back measures showed more frequent exercise effects and better participant-independent discrimination than thigh-derived measures. Although the combined configuration captured additional trunk-thigh relationships, it did not improve classification performance beyond the upper-back-only configuration.

After false-discovery-rate adjustment, 12 of the 48 prespecified measures differed among exercises, and all were kinematic. These comprised seven upper-back, three thigh, and two paired trunk-thigh measures. No timing or repetition-consistency measure remained significant. Under the controlled loading and cadence conditions, exercise differences were therefore represented mainly by segmental excursion, recorded angular-speed patterns, and trunk-thigh relationships.

The classification results supported this sensor hierarchy. Balanced accuracy was 65.2% for the upper-back-only configuration, 63.0% for the combined configuration, and 42.8% for the thigh-only configuration. Adding upper-back measures to the thigh-based configuration improved balanced accuracy by 20.3 percentage points. In contrast, adding thigh-derived and paired measures to the upper-back-based configuration did not improve performance. These findings indicate that the upper-back IMU captured most of the exercise-discriminating information available from the tested configurations.

Participant-related findings were limited. No association with total knee-extension force remained significant after multiplicity adjustment. Four differences between women and men were identified in back-squat thigh kinematics in the primary analysis, but these findings were not retained in the non-parametric sensitivity analysis and were confounded by the use of different prescribed loads.

4.2 Exercise-Specific Kinematic Assessment

The greater number of significant upper-back measures indicates that trunk motion was the principal source of differentiation among the three exercises. These measures included sagittal excursion, recorded sagittal angular-speed

descriptors, sagittal velocity-profile ratio, and mean angular speed in the frontal and transverse planes. The sagittal-plane findings are consistent with biomechanical evidence that squats and deadlifts differ in their relative trunk, hip, and knee movement demands [1, 2].

The clearest distinction occurred between the deadlift and the two squat variations. The deadlift showed greater trunk excursion and recorded angular speed, consistent with its greater reliance on trunk and hip movement. Previous kinematic analyses have similarly identified differences in trunk and lower-limb movement between squats and conventional deadlifts [2]. Research comparing deadlift techniques has also shown that trunk and lower-limb kinematics vary with exercise form [1].

The classification results supported the distinctiveness of the deadlift movement pattern. Deadlift recall was 82.6% with the upper-back-only configuration and 89.1% with the combined configuration. Front squats and back squats were more frequently confused, indicating greater overlap between the two squat variations.

Bar position can alter trunk posture and mechanical demands during squatting [3–5]. Oshikawa et al. reported greater lumbar lordosis during the front squat than during the back squat at the same absolute load [5]. In the present study, selected upper-back measures differentiated the two squat variations. However, their lower classification recalls indicate that these differences were not sufficiently consistent across participants for strong discrimination. Variation in anthropometry, mobility, stance, movement depth, and training experience may have contributed to this overlap.

The thigh IMU showed more selective exercise sensitivity. Significant thigh measures were confined mainly to mean recorded angular speed and velocity-profile ratio, whereas sagittal excursion and recorded speed extrema did not differ among exercises. This pattern suggests that the standardized protocol produced broadly similar thigh excursion while retaining differences in the angular-speed profile of the movement.

Nevertheless, the thigh-only configuration achieved a balanced accuracy of 42.8%, indicating limited participant-independent discrimination. This finding illustrates the distinction between statistical sensitivity and predictive utility. A measure may differ among exercises at the group level without providing sufficiently distinct or consistent information to classify individual observations.

4.3 Added Value of the Dual-IMU Configuration

Both paired trunk-thigh measures differed significantly among exercises. Normalized excursion difference represented the relative contributions of trunk and thigh movement, while trajectory correlation described the similarity of their sagittal-plane trajectories. The combined configuration therefore provided intersegmental information that was not directly available from either sensor alone.

This additional information did not improve classification relative to the upper-back-only configuration. The combined configuration differed from the upper-back-only configuration by – 2.2 percentage points in balanced accuracy and – 2.4 percentage points in macro-F1, with both confidence intervals including zero. The thigh-derived and paired measures therefore provided little incremental predictive information once upper-back measures were included.

These findings show that significant group-level differences in paired measures do not establish the superiority of a dual-sensor system. The paired measures may capture meaningful intersegmental variation while overlapping with information already represented by upper-back motion. Additional sensors and features may also introduce measurement and between-participant variability without improving generalization.

For the exercises and outcomes examined here, the results support sensor parsimony. A single upper-back IMU reduces placement, synchronization, processing, and user-burden requirements while providing the strongest overall assessment capability among the tested configurations. A dual-IMU configuration may still be appropriate when the purpose is to

examine relative trunk-thigh excursion, intersegmental trajectory similarity, or thigh-specific movement rather than exercise discrimination alone.

4.4 Participant-Related Findings

No association between total knee-extension force and the IMU-derived measures remained significant after sex-specific FDR adjustment. Under the standardized submaximal conditions, movement patterns may have been influenced more strongly by task requirements than by isolated knee-extension force. Squat and deadlift kinematics may also depend on other factors, including anthropometry, mobility, hip and trunk strength, training experience, and movement strategy.

Four thigh sagittal-plane measures during the back squat differed between women and men in the primary analysis, with large standardized effects. However, these findings did not remain significant in the separately adjusted Mann-Whitney sensitivity analysis. More importantly, women and men performed the exercises using different prescribed absolute loads. The observed differences may therefore reflect loading, body size, training experience, sex, or interactions among these factors.

These findings should be considered exploratory and should not be used to establish sex-specific reference values or monitoring thresholds. Studies using loads normalized to individual capacity and larger participant samples are required before participant-specific interpretation is warranted.

4.5 Implications for Low-Complexity IMU Assessment

Wearable IMUs provide a portable approach to field-based movement assessment, but their outputs depend on sensor position, attachment, orientation, recording characteristics, and the selected outcome measures [7, 9]. Sensor position has been shown to influence range-of-motion estimates during squatting, emphasizing the importance of standardized placement procedures [24].

Among the configurations examined, the upper-back location provided the best balance between system simplicity and exercise-specific information. Upper-back excursion, recorded angular-speed measures, and velocity-profile ratio may therefore be useful candidate outcomes for describing squat- and deadlift-related movement patterns. Thigh-derived measures may be more relevant when lower-limb angular-speed characteristics are of specific interest, while paired measures may support the assessment of intersegmental movement.

The upper-back-only balanced accuracy of 65.2% exceeded the 33.3% reference for uniform random guessing but represented moderate rather than high discrimination. The present findings demonstrate meaningful exercise-specific information capture, not a fully developed exercise-recognition system. The results also do not establish measurement validity against laboratory-based motion capture.

Future studies should evaluate test-retest reliability, agreement with reference motion-capture measurements, and responsiveness to changes in load, cadence, fatigue, and technique. External validation in larger and more diverse populations is also required before the measures are used for individual monitoring or feedback.

4.6 Limitations and Future Directions

Several limitations should be considered. First, standardized absolute loads were used rather than loads normalized to body mass or individual strength capacity. Although this supported a controlled submaximal protocol, it limited the assessment of load-dependent kinematics. Women and men also performed the exercises using different prescribed loads, preventing sex-related effects from being separated from loading effects.

Second, the exercises were completed in a fixed rather than randomized or counterbalanced order. Exercise-specific differences may therefore have been partly influenced by familiarization, fatigue, adaptation to the prescribed cadence,

or progressive sensor movement. Exercise and order effects could not be separated.

Third, the IMU-derived measures were not validated against a reference system such as optical motion capture. The present findings demonstrate sensitivity to exercise differences and participant-independent discrimination, but not measurement accuracy. The measures should therefore be interpreted as segment-level descriptors rather than validated estimates of anatomical joint kinematics.

Future studies should evaluate reliability and criterion validity across participants of different ages and functional abilities, particularly older adults. Additional sensor locations could be examined when the intended outcome requires joint-specific assessment or bilateral symmetry analysis. The framework should also be evaluated across a broader range of exercises, loading conditions, and movement speeds. Further validation would be required before extending the system to applied tasks such as workplace movement assessment, technique evaluation, or detection of potentially relevant movement patterns such as dynamic knee valgus.

5 CONCLUSIONS

Among the tested configurations, a single upper-back IMU provided the strongest exercise-specific kinematic assessment capability during cadence-controlled, low-load front squats, deadlifts, and back squats. Upper-back measures showed broader sensitivity to exercise differences and better participant-independent discrimination than thigh-derived measures. Although the dual-IMU configuration captured additional trunk-thigh excursion and trajectory relationships, it did not improve classification performance beyond the upper-back-only configuration. These findings support the upper back as the preferred single-sensor location when minimizing system complexity is a priority. However, the moderate classification performance and absence of criterion validation limit immediate application to individual monitoring or feedback. Further research should establish reliability and validity against reference motion capture across different loads, movement speeds, age groups, and exercise conditions.

Declarations

Disclosure of funding and conflicts of interest

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Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained from the Human Research Ethics Committee of The University of Hong Kong (HREC reference: EA240113). All participants provided written informed consent prior to participation.

Clinical trial number

Not applicable.

Consent for publication

Not applicable. This manuscript contains no identifiable personal data. The figure illustrating sensor placement (Fig. 1) shows the sensor configuration on a participant whose facial features have been fully anonymized (face obscured), thus no individual can be identified.

Competing interests

The author declares no competing interests.

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Author Contribution

Samson Nanxin Zhang is the sole author of this manuscript and was responsible for the conceptualization, methodology, investigation, data curation, formal analysis, visualization, and interpretation of the findings. He also prepared the original draft, critically reviewed and revised the manuscript, and approved the final version for submission.

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Data Availability

The datasets generated and/or analysed during the current study consist of inertial measurement unit (IMU) data collected from the trunk and thigh regions, together with continuous video recordings used to validate exercise protocols during post-processing. Due to the inclusion of participant data and privacy considerations, the datasets are not publicly available. The datasets are available from the corresponding author upon reasonable request and subject to applicable ethical and data protection requirements.

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Figures

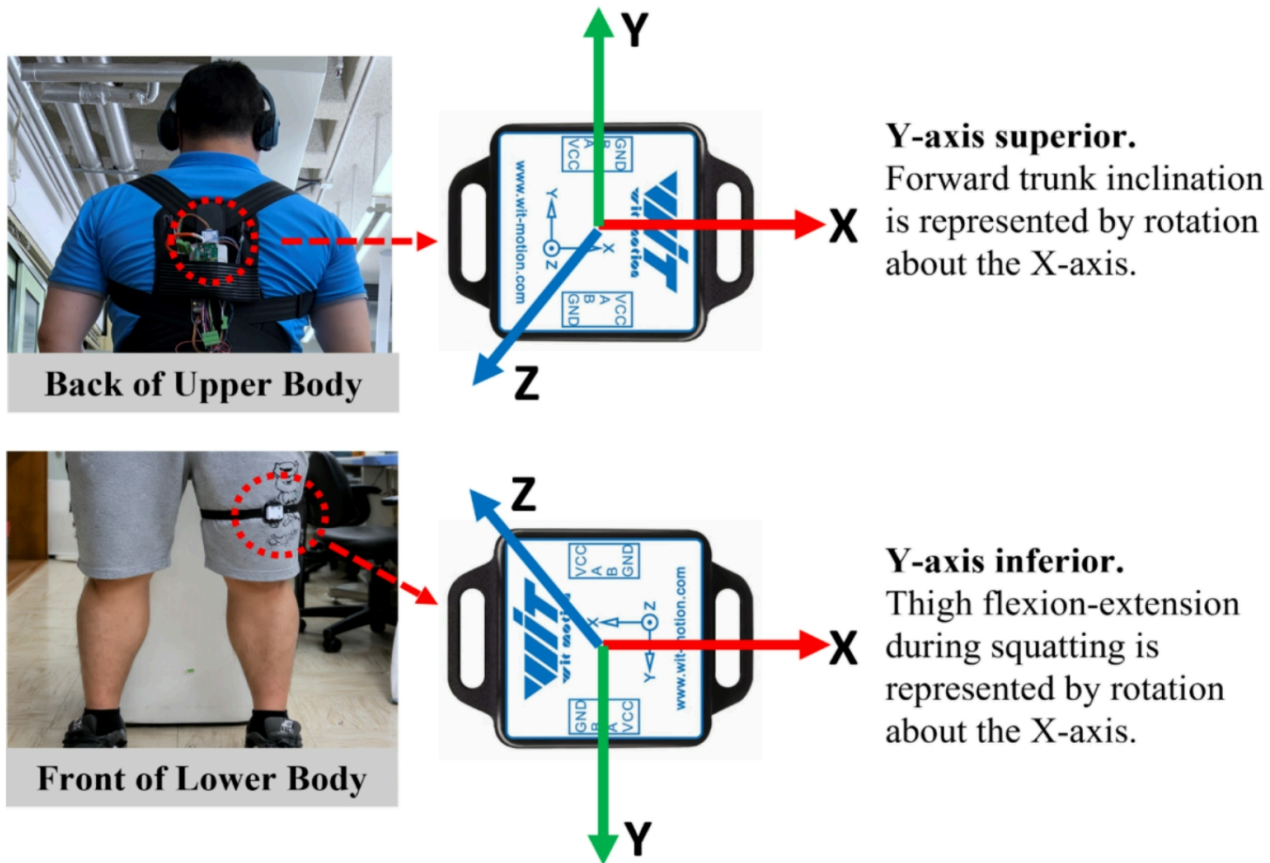


Figure 1

Placement and axis orientation of the upper-back and left-thigh inertial measurement units.

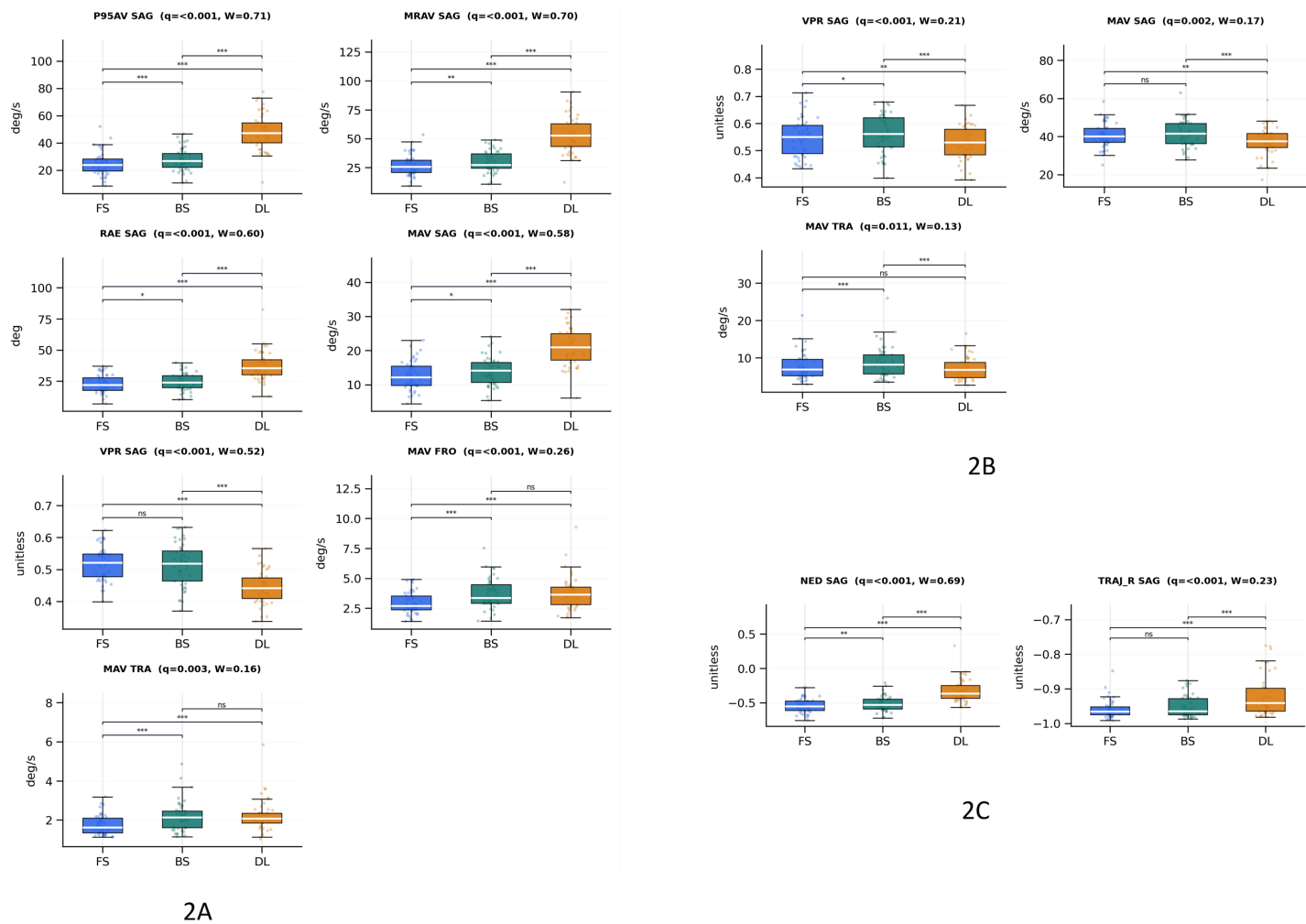


Figure 2

2A. Upper-Back-Derived Measures.

2B. Thigh-Derived Measures.

2C. Paired Trunk-Thigh Measures.

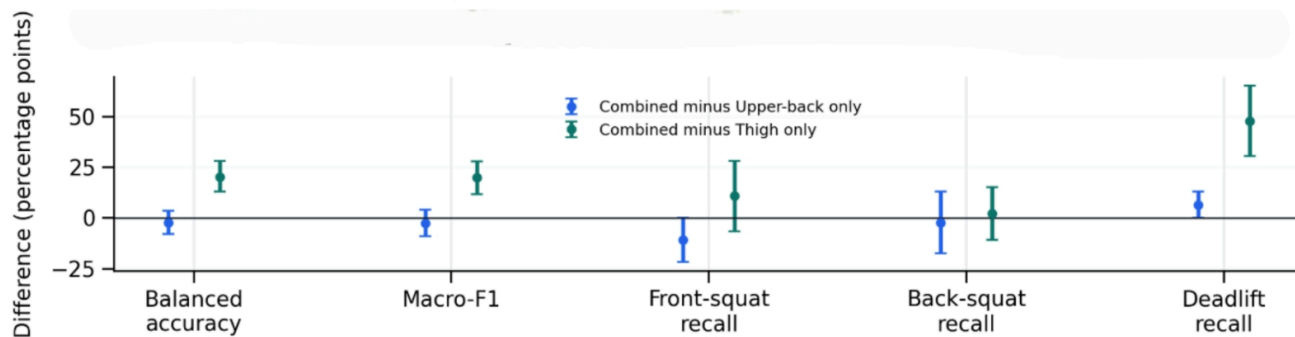


Figure 3

Incremental exercise-classification performance of the combined upper-back-thigh configuration relative to the single-IMU configurations

Supplementary Files

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