Brock Biomechanics Team (*Xsens Challenge*)

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***Abstract*—The primary objective of this work was to implement a methodological approach that can be used in a clinical setting to assess power and kinematic variability across repetitions of four movement tasks. To achieve this, gross power estimates were calculated. Bilateral asymmetries were assessed using kinematic data of joint angles, and velocities during movement. Specifically, continuous relative phase was used to assess the coordination across all cycles of the movement. Finally, a supplementary principal component analysis was used to provide reconstructions of representative movement styles and relevant time-varying indicators of performance. Our approach can be easily implemented in a clinical setting with limited knowledge of biomechanical modelling and aims to enhance rehabilitation and sports performance.**

Keywords—biomechanics, IMUs, power, kinematics, continuous relative phase, principal component analysis

I. Introduction

Power is the rate of doing work [1] and is a combination of force multiplied by velocity, to overcome resistance in the shortest duration of time. It is the ability to produce high velocities at a given load to perform fast, forceful, and propulsive movements. As we age, or injuries occur, our ability to exert maximum power diminishes. Power training in a clinical setting could help improve the process of rehabilitation for an elite athlete recovering from a debilitating injury [2], the recovery of lower body power to assist in gait and functional independence for someone with Parkinson's disease [3], or returning to a physically demanding occupation [4] following a workplace injury.

In the assessment of coordinated movements, continuous relative phase (CRP) angles provide an estimate of the time varying relationship between two moving segments or joints [5]. In the estimation of cycle-cycle coordination variability, the standard deviation of a CRP angle, often referred to as Deviation Phase (DP) captures the variability in one's motor coordination patterns during repeated tasks [5]. Additional approaches which are useful in the calculation of motor variability, and the reconstruction of representative motor movements are principal component analysis (PCA), and single component reconstruction (SCR). PCA approaches have been particularly useful for visualizing motor task variability [6-7].

The objective of this work was twofold: 1) to use IMU data to develop a simple and effective approach to help clinicians assess power generated during rehabilitation exercise and 2) to determine the repeatability of the task to effectively maximize the therapy process.

II. Methodology

A. Data Acqusition

A single participant (height: 1.6 m, mass: 55 kg) completed four movement tasks. The tasks included a Back Squat (five cycles at each of seven loading conditions: 20, 30, 40, 50, 60, 70, 80 kg), a Bench Press (five cycles at each of five loading conditions: 15, 25, 35, 40, 45 kg), a Ball kick (seven cycles), and a Ball throw (six cycles). During all movements full body motion capture data were acquired using an XSens MVN Awinda system that included 17 sensors on individual segments with a sample rate of 60 Hz.

B. Data Pre-Processing

Kinematic data were pre-processed within the XSens MVN software using the HD Reprocessing Tool. After re-processing, all trials were exported as .xlsx files, without down sampling, for subsequent offline analysis in MATLAB 2020b (The MathWorks Inc.).

C. Primary Offline Analyses

i. Power Analysis

For the analysis of power, data from all four motions were first partitioned visually using specific onset and offset event characteristics (i.e., mean hand vertical displacement – Bench Press and Squat, peak right shoulder external rotation to peak right shoulder flexion – Throw, peak acceleration of right toe in x-axis – Kick). Power for all four motions was then calculated using the following formula:

$$Power = Force * Velocity$$

For the Bench Press and Squat motions, force was defined as the product of the mass of the load lifted by the acceleration of the load (mean acceleration of the left and right hands at each frame), and the velocity was defined as the mean velocity in the z-axis of the left and right hands at each frame. For the Throwing motion, the force was defined as the product of the mass of the ball by the Euclidean norm of the acceleration of the throwing hand (right hand) at each frame. The velocity was defined as the Euclidean norm of the velocity of the right hand at each frame. For the Kicking motion, the power was calculated at the peak x-axis acceleration of the kicking toe (right toe). Force was defined as the mass of the ball by the Euclidean norm of the acceleration of the right toe, and velocity was defined as the Euclidean norm of the velocity of the right toe at the corresponding frame. From the power calculations, peak power of all five repetitions at each weight for the Bench Press and Squat and for each Throw and Kick were defined (see *Appendix A - Figure A1).*

ii. Bilateral Variability: Continuous Relative Phase

CRP and DP were calculated using bilateral data from the knee (Squat) and elbow (Bench Press). To calculate CRP, time-varying flexion-extension (ZXY) data were utilized, including any previously obtained onset and offset event markers from any previous analyses. Next, joint angular velocity was calculated by taking the derivative of the elbow and knee angle using the central finite difference method. All joint angle and angular velocity data were time-normalized 0-100% cycle. Further, the joint angle and angular velocity were phase-normalized from -1 (min) to +1 (max) [8]. From the phase normalized joint angle and angular velocity, phase angles were calculated at each time point of the cycle using a four-quadrant inverse tangent function and defined all the angles from the right horizontal axis [9]. All phase angles ranged from 0-180 degrees. CRP values were calculated by subtracting the right elbow from the left elbow for the bench press trials and the right knee from the left knee for the squat trials. The mean CRP was calculated from the ensemble of all five repetitions for each load. The DP was calculated by taking the standard deviation across all cycles (n=35 squat, n=25 bench press). Positive CRP values indicate that right side angular movements precede left side ones, negative values indicate the opposite. Higher DP values indicate a larger cycle-cycle variability.

iii. Kinematic Analyses

To further analyze kinematics and bilateral symmetries, calculations of elbow flexion range of motion (ROM) of the Bench Press and knee joint flexion ROM of the Squat were assessed. For the Bench Press, left and right-hand positions were chosen as event markers to define repetitions then maximum and minimum left elbow flexion vs right elbow flexion were used to define ROM. Bilateral asymmetries were reported in *Appendix A - Table A1* where final positive values indicate larger ROM of the right and a final negative value indicates greater ROM of the left. The same process was carried out for the Squat movement, except maximum and minimum knee flexion ROM was defined. In addition to these ROM measures, additional time-normalized measures were obtained for the Squat and Bench Press. These measures include the height of the barbell relative to the sternum (T8) during the Bench Press, and the absolute height of the barbell during the Squat. Finally, the peak vertical velocity of the barbell was computed for all Squat and Bench Press loading conditions.

D. Supplementary Offline Analyses

To complement the primary offline analyses, supplementary analyses were completed with the aim of developing movement quality reports for each movement type. The aim of these reports were to provide relevant time-varying (i.e., video) indicators of performance, relative to visual feedback being depicted on a reconstructed avatar. If possible, a data-driven approach was taken to reconstruct *representative* movement patterns for each trial and condition.

For the analysis of the Squat and Bench Press (*Appendix B*), data were first partitioned into individual time-normalized (0-100%) cycles (n = 35 – Squat, n = 25 – Bench Press) mirroring previous analyses (*Section C.iii*). Next, positional data were represented relative to either the 3D location of the right foot (Squat) or pelvis (Bench Press). Finally, specific time-series outcomes (3D segment position, velocity, orientation, and ZXY joint angles) for all body segments/joints were amplitude normalized ($-1.5 \le x \le 1.5$) and used to generate an input data matrix for further PCA. The input matrix for each PCA was structured in the following manner:

$$\begin{bmatrix} d(x,y,z)^{1}_{1-101} & v(x,y,z)^{1}_{1-101} & a(x,y,z)^{1}_{0-101} & \theta(rx,ry,rz)^{1}_{1-101} \\ d(x,y,z)^{2}_{1-101} & v(x,y,z)^{2}_{1-101} & a(x,y,z)^{2}_{1-101} & \theta(rx,ry,rz)^{2}_{1-101} \\ d(z,y,z)^{n}_{1-101} & v(x,y,z)^{n}_{1-101} & a(x,y,z)^{n}_{1-101} & \theta(rx,ry,rz)^{n}_{1-101} \end{bmatrix}$$

Such that, *d* represents all 3D segment displacements (m), *v* represents all 3D segment velocities (m/s), *a* represents all 3D segment accelerations (m/s^2), and θ represents all 3D joint angle time-series data (°). Within this matrix structure each row contained 27573 data points (101 frames x 273 variables), with the number of rows being dictated by the number (*n*) of cycles for each movement type (n = 35 – Squat, n = 25 – Bench Press).

Once constructed, PCA was then used as a holistic approach to discern the primary modes of cycle-cycle variation present within each data matrix. The number of PCs retained explained >90% of the variation within each dataset. To interpret the association of each PC score relative to the lifted load for each condition, linear regressions were completed and R^2 statistics were computed (*Appendix B – Figure B1*). PC scores demonstrating a strong association with the lifted load were then interpreted using a SCR approach [6] to reconstruct the representative movement patterns (i.e., 3D positions, velocities, accelerations, and joint angles) for each loading condition. These reconstructions were then used to develop a movement report (*Appendix B – Figure B2*) which demonstrates the kinematic adaptations which is linearly *scalable* across the range loading conditions, and mirrors similar approaches in the analysis of overground walking (e.g. [7]).

For the analysis of the Throw and Kick (*Appendix B – Figures B3-4*), a similar approach as the one noted above was taken to develop a representative data matrix for each time-normalized cycle (n = 6 – Throw, n = 7 – Kick); however, given the lack of data (i.e., number of cycles, *n*) for these movements PCA, and SCR were not completed. Instead, a mean movement waveform was estimated, and used to generate visual Throw and Kick reports, which can be used on a cycle-cycle basis. For the Throw, this report demonstrates the 3D trajectory taken for the throwing motion, the location of the peak Euclidean Norm hand velocity along this trajectory, a visual depiction of the estimated Ball power, and an estimate of Throw “Inefficiency” which is related to the length of the 3D ball path, relative to the mean reconstructed throwing movement. For the Kick, this report takes a similar form; however, given the extremely transient interaction between the toe and ball, Ball power is estimated at a single point of contact (estimated using peak anterior toe acceleration – depicted in blue *Appendix B – Figure B4*), and Kick "Inefficiency" is related to the 3D foot path, relative to the mean reconstructed Kick. The aim of each report (Throw and Kick) is to provide a comprehensive visual representation of Throw or Kick cycle-cycle performance.

III. RESULTS

A. *Primary Offline Analyses*

i. *Power Analysis:*

Results support our primary objective of developing an effective approach to compute power generated during movements (*Appendix A – Figure A1*). Our results revealed that the greatest peak power was generated during Bench Press and Squat movements with an intermediate load (Bench: 35-40 kg, Squat: 50-60 kg) as compared to the higher and lower loads. The Kick movement generated the greatest peak power across all movements (500 W) and the throw generated the least peak power (200 W). Inconsistencies in peak power generated were observed across all movements as each repetition of the movement generated different peak powers. Generally, heavier loads experienced a drop in peak power as cycles progressed.

ii. *Bilateral Variability: Continuous Relative Phase*

The analysis of variability for the Squat and Bench Press revealed greater variability in the concentric phase compared to the eccentric phase of the lift of both the Squat and Bench Press. For 50, 70 and 80 kg sets of the squat the participant displayed a right knee leading strategy at 75-85% of the rep cycle. For the 15, 25, 35 and 45 kg the participant displayed a right elbow leading coordinative strategy during 90-100% of the rep cycle. Generally, larger asymmetries were observed during the concentric phase of the heavier Squat and Bench Press loads.

iii. *Kinematic Analyses:*

To further support our secondary objective of assessing the repeatability of a task across repetitions, our kinematic analyses revealed differences between ROM in the left and right knee (Squat) and elbow flexion (Bench Press) (*Appendix A – Table A1)*. Bilateral asymmetries in the Squat as greater knee flexion ROM in the left side are observed with lower loads and a great knee flexion ROM are associated with higher loads. However, the Bench Press elbow joint ROM is consistently greater on the right-side and an increased joint angle ROM associated with lower loads compared to the ROM achieved with heavier loads. In addition to these findings, our analyses suggested a marked reduction in movement velocity with added load (*Appendix A – Table A2*) including a general decrease in Squat depth with added load, and a general increase in Bench Press depth with added load (*Appendix A – Figure A3*).

B. *Supplementary Analyses*

In the analysis of the Squat and Bench Press, 12 and 10 PCs were retained, respectively, which explained >90% of the variance within each dataset. For both movements, PC1, which explained the largest amount of variance (43.3% - Squat, 50.3% - Bench Press), demonstrated a strong positive relationship with the lifted load (R^2 = 0.94 - Squat, R^2 = 0.83 – Bench Press). Therefore, for both the Squat and Bench Press the PC1 score was utilized as a scalable factor in a single component reconstruction framework to visualize the effects of added load on a representative avatar and relevant time-series outcomes related to segment displacement, velocity, power, mean R/L joint angle and asymmetry (*Appendix B*).

For the Throw and Kick, dynamic visualizations were developed using the mean waveform data. These visualizations mirror those commercially developed for the analysis of elite baseball pitching kinematics (ProPlayAI, Toronto, Ontario, CA) and present time-series data related to ball power and ball path inefficiency. With additional data, representative of some physiological meaningful phenomenon (e.g., fatigue, skill-level, etc.), these animations could be scaled and reconstructed in the same manner as the Squat & Bench Press (*Appendix B*).

IV. CLINICAL RELEVANCE & APPLICATION

Our methodological solutions were specifically designed to be efficiently applied to clinical settings as our approach is innovative, and easily implemented and interpretable. Our results show peak power outputs across all reps and loads for each of the four movements. Peak power generated across repetitions depicts variability across the entire series of cycles. From a performance perspective, the athlete would want consistent peak power outputs across repetitions, once the power drops to 90-95% peak power the set is ceased and is an indication of fatigue, as fatigue consequently affects power output [10]. Our approach also calculates a kinematic analysis of ROM of the knee joint during a squat and elbow flexion during the bench press between the left and the right sides. Lastly, our CRP/DP analysis shows coordination changes of the Squat and Bench Press by comparing the bilateral joint kinematics of the elbow and knee. These analyses specifically allow for an easily interpretable output to discern which joint may be leading/lagging (i.e., mean CRP), and which *portion* of the movement cause is most variable (i.e., mean DP). Collectively, the ROM and CRP/DP analyses can depict asymmetries between the left and the right side of the body during movement. This is clinically important as the magnitude of inter-limb asymmetry during injury recovery could indicate favoring the injured side or from a performance aspect could increase the likelihood of injury [11].

V. DISCUSSION & FUTURE DIRECTIONS

A. *Power Generation Across Movement Tasks*

Power is the ability to produce high velocities at a given load to execute a forceful movement. In rehabilitation and performance, it is ideal to increase the power produced during a movement without compromising form. It is also imperative that the patient or athlete perform the movement with the same concentric velocity throughout repetitions. Our approach assesses the peak power generated comparative across all repetitions in an offline analysis that is visually displayed and ready for interpretation by the clinician. Movements that required low loads, but high velocity (Throw and Kick) were able to generate relatively high peak powers compared to the Squat and Bench Press (*Appendix A – Figure A1*).

B. Rationale for Computation of Power

The power analysis was informed by previous research investigating the validity of wearable sensors to measure power generated during bench press and squat movements [12]. Similar to previous work, acceleration data was acquired from relevant segments for each movement of each frame, and instantaneous force was calculated as the product of the mass of the load (Bench Press, Squat) or ball (Throw, Kick) by the acceleration of the relevant segment [12]. Ideally when tracking the displacement of the barbell during the Bench Press or Squat, a sensor on the bar could be implemented [12]; however, the dataset provided was limited to sensors fixed exclusively to the participant. Therefore, to track the displacement of the bar during both the Bench Press and Squat movements, the mean of the left- and right-hand displacement in the z-axis were implemented as these will most closely resemble the barbell path due to the direct contact between the hands and the bar throughout the entirety of these movements. Using mean hand displacement accounted for any asymmetry between left- and right-hand displacements to resemble the centre of the bar. While additional estimates of joint loading and power can be accomplished with advanced biomechanical modelling, our solution was designed with patients, and athletes, in mind.

C. Repeatability Across Repetitions and Sets

As it is important that power generation remain consistent across movements, it is also critical that the power generated and kinematics (e.g., ROM) of the movement are repeatable across repetitions and sets. Our computational approach of peak power (force*velocity) demonstrates some cycle-cycle variability in peak power for all movements. We explored this variability by implementing an analysis of R/L knee and elbow ROM, CRP, and DP. The ROM comparison evaluates gross differences in peak angular displacement; however, the CRP and DP analyses afford a deeper understanding of the coordination of such flexion-extension movements. Our analyses note a larger R/L CRP asymmetry with larger lifted loads, resulting in a large variability (DP) during the concentric phase of the Squat and Bench Press movement. These changes may, in part, be associated with changes in movement velocity or Squat and Bench Press Depth (*Appendix A – Figure A3*)

D. Use of Supplentary Analyses in a Sport or Clinical Setting

The data-driven (i.e., PCA and SCM) approach in the visualization of the Squat and Bench Press has many advantages. First, the approach taken is not intrinsically biased to assess any specific outcome/parameter, but rather uses any acquired kinematic data to reconstruct relevant modes of variation. In this way, any variation captured in a given dataset (i.e., load, sex, skill-level, rehabilitation status, etc.) may be assessed in a *holistic* manner to facilitate the animation of any reconstructed avatar, or time-varying parameter of interest. This facilitates the development of a kinematic model which is scalable across a biologically relevant parameter, mirroring previous analyses in overground walking (N. Troje: BioMotion Lab). These reconstructions may be used in further analyses including animation or musculoskeletal modelling approaches. Although such reconstructions are undoubtedly useful in a clinical or performance setting, these approaches may also be superimposed with other supervised or unsupervised machine learning approaches to further partition or cluster the dataset, if desired. Our novel analysis of the Throw and Kick developed time-varying visualizations of position, velocity, and power, including a novel measure of Throw/Kick inefficiency. With further data our aim would be to use this approach to partition the kinematics necessary to facilitate different pitch (i.e., fast ball, curve ball, sinker, etc.) and kick (i.e., strike, corner, etc.) types.

E. Future Directions

This proposed workflow (and donated Xsens IMU equipment) could greatly contribute to research and development at Brock University. In the department of Kinesiology, these IMU systems can be used to track work-related injury risk (*Neuromechanics and Ergonomics Lab, PI: M.W.R. Holmes*), rehabilitation (*Spine Biomechanics and Neuromuscular Control Lab PI: S.M Beaudette*), and sport performance (*On Ice Performance Lab, PI: K.L. Lockwood*). The listed authors represent a group of representative graduate students within each of these laboratories, with keen interest in implementing the primary and secondary analyses (and donated equipment) into their Thesis and Dissertation research projects.

VI. Conclusions

- IMU based velocity and position data are critical to calculate peak power generated during rehabilitation movements for clinicians and coaches.
- Our CRP/DP analysis is an accurate representation of coordination changes by comparing bilateral joint kinematics.
- PCA/SCR are useful biomechanical modelling tools to visualize motor task variability in conjunction with power.

References

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APPENDIX A – PRIMARY ANALYSES

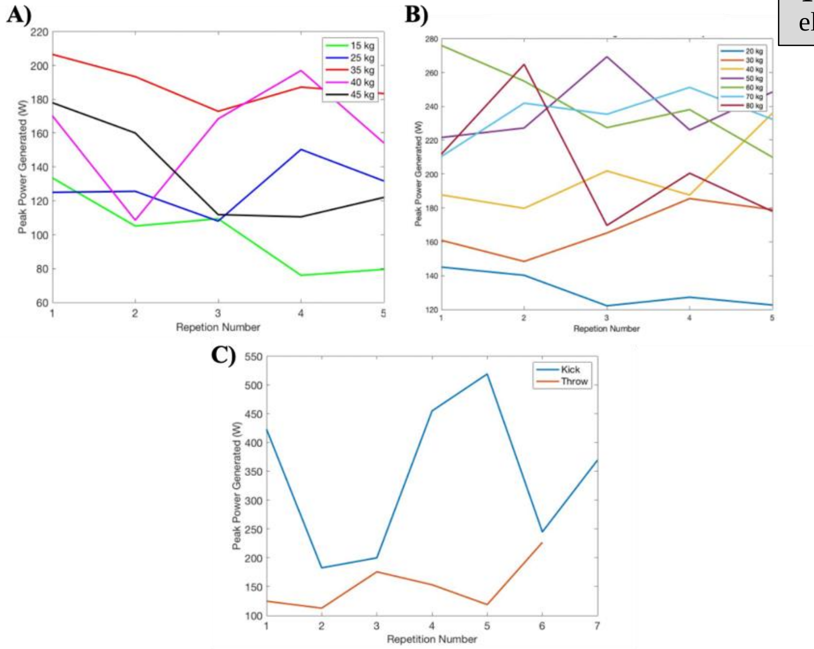


Figure A1: Peak power for the **A)** Bench Press, **B)** Squat and **C)** Throw/Kick.

Table A1: Bilateral comparison of knee joint ROM (°) of Squat and elbow flexion ROM (°) of Bench Press for all loads and repetitions.

Load	Repetition Number				
	1	2	3	4	5
Knee Joint Angle ROM – Left vs. Right					
20 kg	-1.19	-1.69	-1.06	-1.19	-1.53
30 kg	-2.01	-1.72	-1.68	-1.59	-2.46
40 kg	2.01	-0.01	0.40	1.76	0.86
50 kg	0.77	-0.24	0.05	0.66	0.87
60 kg	2.12	1.48	1.30	-0.43	1.73
70 kg	1.60	0.58	0.31	0.06	0.69
80 kg	1.80	0.83	0.65	1.76	1.44
Elbow Joint ROM – Left vs. Right					
15 kg	6.86	9.41	8.04	9.00	6.08
25 kg	4.89	5.95	5.10	5.54	-0.69
35 kg	-2.63	0.07	1.59	1.05	4.43
40 kg	4.06	6.59	4.33	3.91	7.36
45 kg	0.77	0.03	4.78	0.59	3.83

**Note: positive values refer to larger right knee ROM compared to left knee*

Table A2: Peak barbell vertical velocity of the Squat and Bench.

Load	Repetition Number				
	1	2	3	4	5
Peak Barbell Vertical Velocity (m/s) – Squat					
20 kg	1.76	1.74	1.71	1.75	1.73
30 kg	1.57	1.61	1.61	1.61	1.58
40 kg	1.40	1.39	1.50	1.48	1.45
50 kg	1.31	1.29	1.33	1.32	1.27
60 kg	1.18	1.16	1.12	1.11	1.10
70 kg	1.02	1.00	1.00	0.99	0.99
80 kg	0.87	0.93	0.84	0.79	0.82
Peak Barbell Vertical Velocity (m/s) – Bench Press					
15 kg	1.50	1.48	1.53	1.21	1.28
25 kg	1.16	1.21	1.12	1.09	1.03
35 kg	0.81	0.78	0.78	0.80	0.79
40 kg	0.72	0.64	0.72	0.75	0.68
45 kg	0.67	0.61	0.54	0.59	0.56

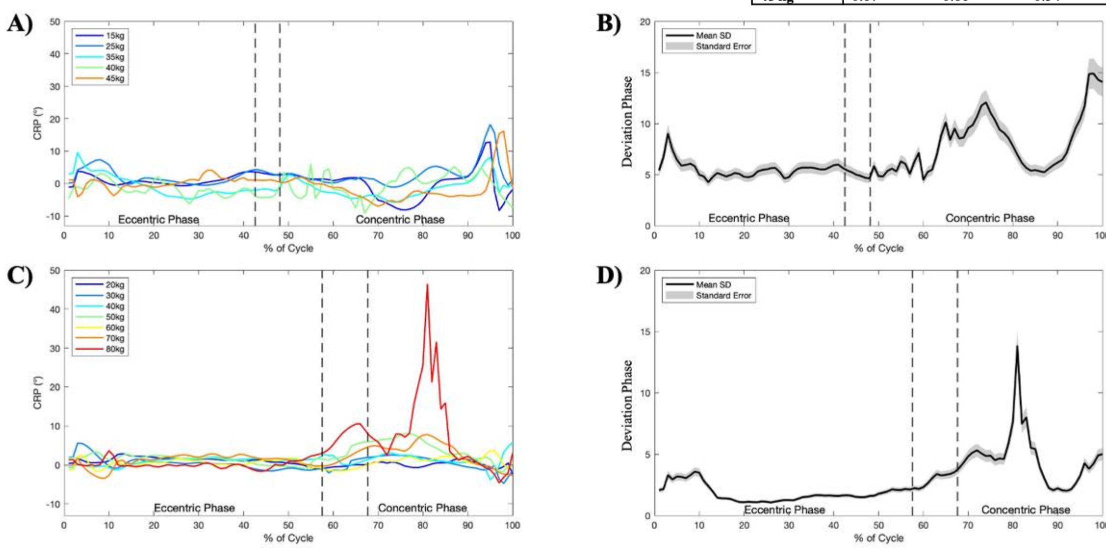


Figure A2: Variability data of CRP (°) and DP (°) across repetition cycle (%) of the eccentric and concentric phase of the movement for the **A.** CRP of the Bench Press **B**. DP of the Bench Press, **C.** CRP of the Squat, **D**. DP of the Squat

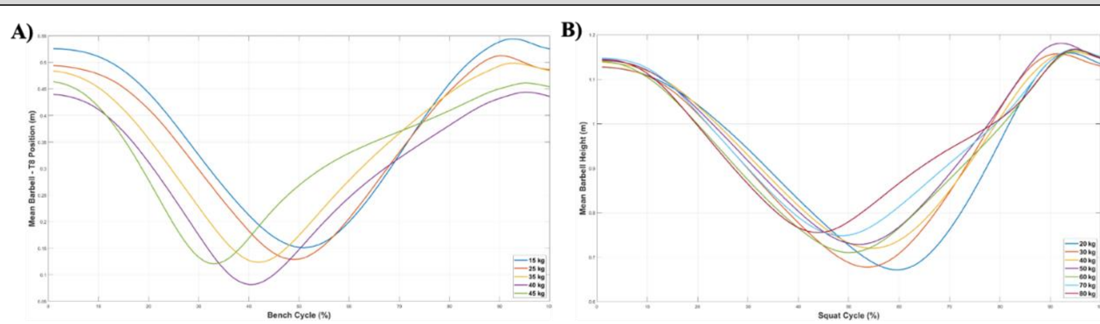
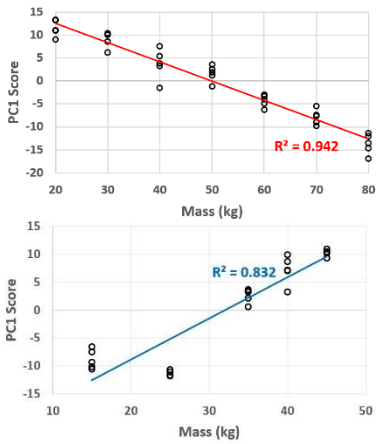


Figure A3: Mean barbell displacement time series data of the **A.** Bench Press (relative to the sternum) **B**. Squat

APPENDIX B – SUPPLEMENTARY ANALYSES (CLICK IMAGES TO ACCESS VIDEO LINKS)

Principal Component	Explained Variance (%)	Cumulative Explained Variance (%)	Coefficient of Determination (R^2) vs. Load
PC1*	**43.3**	**43.3**	**0.94**
PC2	21.8	65.1	0.00
PC3	6.1	71.1	0.00
PC4	4.6	75.7	0.02
PC5	2.8	78.5	0.02
PC6	2.4	81.0	0.01
PC7	2.4	83.4	0.01
PC8	1.9	85.3	0.00
PC9	1.4	86.7	0.00
PC10	1.6	87.9	0.00
PC11	1.2	89.1	0.00
PC12	0.9	90.0	0.00



Principal Component	Explained Variance (%)	Cumulative Explained Variance (%)	Coefficient of Determination (R^2) vs. Load
PC1*	**50.3**	**50.3**	**0.83**
PC2	13.3	63.6	0.10
PC3	7.7	71.3	0.00
PC4	5.9	77.2	0.00
PC5	3.2	80.4	0.00
PC6	2.4	82.8	0.01
PC7	2.3	85.1	0.01
PC8	2.0	87.1	0.01
PC9	1.6	88.7	0.00
PC10	1.4	90.1	0.01

Figure B1. Retained PCs for the Squat (left-Red) and Bench Press (Right-Blue), including linear relationship between PC1 and load.

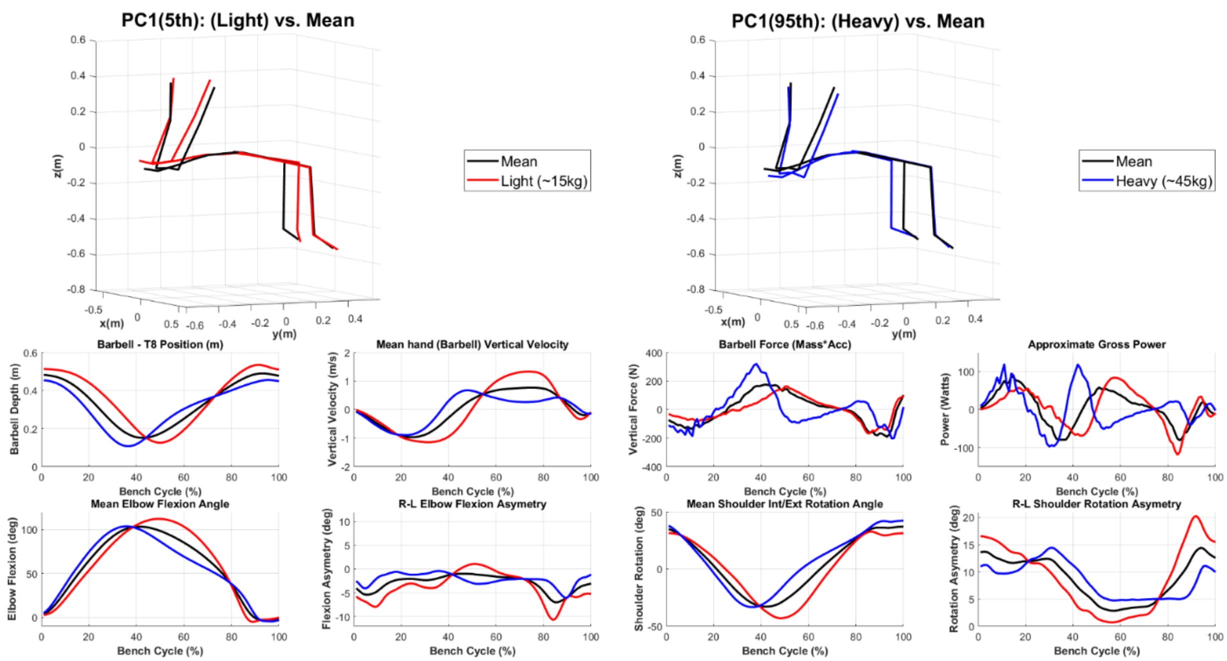
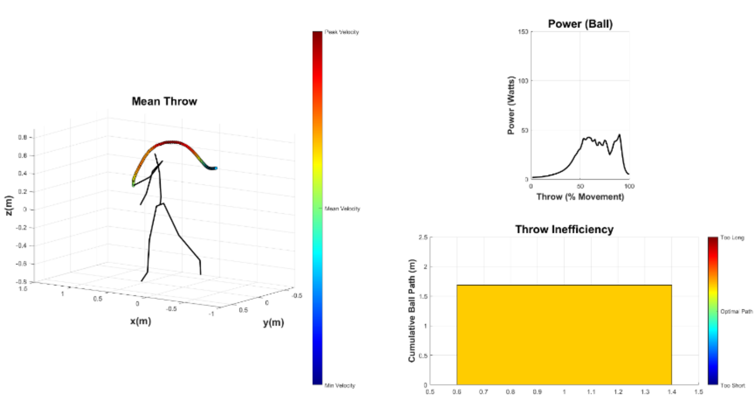


Figure B2. PCA - driven coaching tool demonstrating effects of lifted load (**Video:** https://youtu.be/yCP0_37aAUo)



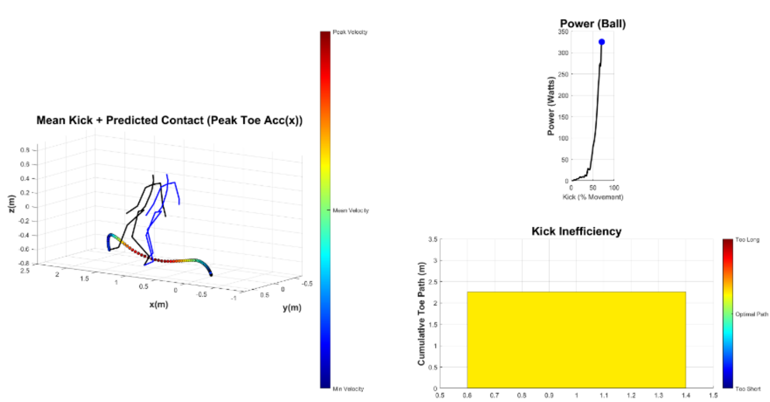


Figure B3. Mean (n = 6) throwing data demonstrating pitch visualization tool (**Video:** https://youtu.be/gIMFVIw1hJ8)

Figure B4. Mean (n = 7) kicking data demonstrating kick visualization tool (**Video:** https://youtu.be/qLLr8N9WT9Y)