Title: A biomechanical approach to evaluate overload and specificity characteristics within physical preparation exercises

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Running Title: Biomechanics of training principles

Word Count: 3987

ABSTRACT

An essential component of any physical preparation programme is the selection of training exercises to facilitate desired performance outcomes, with practitioners balancing the principles of sports training to inform exercise selection. This study aimed to advance biomechanical understanding of the principles of overload and specificity within exercise selection, utilising novel joint kinetic and intra-limb joint coordination analyses. Synchronised three-dimensional kinematic and kinetic data were obtained from six trained male sprinters (100 m PB, 10.64–11.00) performing block starts (competitive motor task) and seven training exercises that encompassed traditionally viewed general and more specific exercises. Results highlighted the challenging nature of exercise selection, with all exercises demonstrating capacity to overload relevant joint kinetic features of the block start. In addition, all exercises were able to promote the emergence of proximal and in-phase extension joint coordination patterns linked with block start execution, although traditionally viewed non-specific exercises elicited greater overall coordination similarity. The current research helps advance biomechanical understanding of overload and specificity, by demonstrating how exercise selection should not solely be based on perceived replication of a competitive motor task. Instead, practitioners must consider how the musculoskeletal determinants of performance are overloaded, in addition to promoting task specific coordination patterns.

KEYWORDS

Strength training, training specificity, biomechanics, coordination, sprinting

INTRODUCTION

Athletic events that require maximal effort over a short period of time (i.e. sprint events), often utilise training methods external to the sport,[1,2] with the goal of developing task-specific neuromuscular strength that can enhance performance of a competitive motor task (sports performance).[3] Strength training, the process of imposing physical loading to increase the capability of the neuromuscular-skeletal system to produce force,[3] is therefore recognised as a vital element in athletes' physical preparation.[4] According to the principle of overload, for an organism to adapt, the biological system must be stressed above habitual levels.[5] Whilst an overload stimulus is comprised of three main components (intensity, frequency and duration),[6] biomechanics research often interprets this principle within the context of intensity, to understand the level of "mechanical overload" in relation to a given sports movement that can inform exercise selection.[7,8] (Kawamori 2014; Okkonen & Hakkinen, 2013). As adaptations are known to be specific to the nature of the training stress, training exercises should also possess relevant biomechanical similarities with a competitive motor task (specificity),[9] especially in regard to contraction type and range of motion.[10]

Biomechanical analysis can offer insight to the underlying kinematic and kinetic characteristics of training exercises, providing coaches with conceptual understanding that guides exercise selection.[11] Whilst studies have quantified external kinetics of training exercises,[12] joint kinetic analyses have afforded greater insight to the musculoskeletal demand of commonly used strength and power training methods.[13,14] However, the nature of musculoskeletal overload and specificity can only be quantified when evaluated against a competitive motor task, of which there is limited research within the sprinting literature, with previous studies only considering external force and electromyography.[8,15]

From a kinematic perspective, coach perception[1,2] and empirical evidence,[16] has suggested that similarity in movement patterns can facilitate sport specific adaptations to strength training and the transfer of training to improved sports performance.[9] The assessment of intra-limb coordination offers a holistic measure of movement similarity by quantifying the interaction between components of the biological system,[17] with previous research adopting measures of coordination to evaluate movement specificity within sports drills[18,19]and lower body strength training exercises.[20] Compared with analysis of single joint angular displacement, intra-limb coordination has been shown to provide a more sensitive measure to investigate differences in lower-limb movement patterns between tasks that have the same functional goal (e.g. leg extension).[20] Whilst elite coaches regularly acknowledge the importance of coordination for maximising training transfer,[2] more research is required to quantify movement specificity from an intra-limb coordination perspective, especially in relation to physical preparation for sprinting.

Despite the common prescription of strength training,[1,2] there is not yet consensus on the best methods for enhancing sprint performance.[21,22] Whilst heavy resistance training is known to improve neuromuscular strength and be integral to enhancing athletic performance,[4] coaches often perceive these exercises to be non-specific and employ more specific methods (e.g. ballistic, plyometric, resisted/ assisted sports movements) to assist the transfer of increased neuromuscular strength to improved sports performance.[1,2] Exercise specificity is often determined based on kinematic similarity with a competitive motor task, with exercises graded on a spectrum from general to specific.[23-25] However, this approach devalues the principle of overload and those exercises promoting neuromuscular-skeletal adaptations that allow an athlete to overcome biomechanical limitations to performance.[26]

The theoretical model of constraints on action explains how the confluence of constraints (organismic, task, environment) determine self-organisation of coordination patterns to satisfy task demands.[27] In relation to physical preparation, altering organismic constraints (e.g. the neuromuscular-skeletal system's ability to exert force) whilst concurrently promoting coordinative patterns functionally linked with task performance, may increase positive training transfer and enhanced athletic performance. Consequently, determining an exercises level of 'specificity' based on kinematic replication alone may be a limited framework to guide exercise selection.

The aim of this study was therefore to advance biomechanical understanding of the principles of overload and specificity within exercise selection, utilising joint kinetic and intra-limb joint coordination analyses. The purpose of this research was to present a biomechanical approach to evaluate overload and specificity characteristics of training exercises, to help inform the process of exercise selection to enhance sports performance. The block start in athletic sprinting was chosen as the competitive motor task for this study as it requires high external force generation, in minimal time, through extensor moment and power of the lower-limb joints,[28,29] and is essential to outcome in the short sprint events.[30]

METHODS

Six male sprinters (mean ± SD: age, 23 ± 4 years; height, 1.82 ± 0.06 m; mass, 78.52 ± 6.91 kg; leg length, 0.90 ± 0.03 m) with 60 m and 100 m personal best times ranging from 6.81-7.08 s and 10.64-11.00 s, respectively, participated in the current study following ethical approval from the university Research Ethics Committee. Informed consent was obtained from all individual participants included in the study. All participants were injury free at the time of data collection.

Experimental Design

A cross sectional study design was implemented to quantify lower limb joint kinematics and kinetics for seven physical preparation exercises that could be compared with the block start, so that joint-level characteristics of overload and specificity could be evaluated. Three dimensional (3D) external force and kinematics were collected at the National Indoor Athletics Centre in Cardiff during three sessions: maximal-effort block starts (S1) and strength and conditioning sessions including back squat and jump squat exercises (S2) and horizontally projected ballistic exercises (S3). The seven physical preparation exercises (Table 1) were selected to encompass both traditionally viewed general (S2: BS_{90}, JS_0, JS_{60}) and more specific (S3: HJ_{BL}, MBD_{BL}, HJ_{SP}, MBD_{SP}) training exercises. All coaches were involved with exercise selection, which incorporated those currently used within their athletes' training programmes.

Experimental Procedures

During S1, each participant performed six maximal effort 10 m sprints from force instrumented starting blocks following a coach prescribed warm up.[28] For S2 and S3, two sets of three repetitions were performed for each exercise following the participant's regular warm up for the particular type of activity to be completed. The exercises in S3 were performed in a randomised order, whereas in S2 all participants performed BS_{90} prior to a randomised order of JS_0 and JS_{60}, allowing each athlete to safely prepare for the greatest external load to be lifted. The external loads lifted during BS_{90} and JS_{60} were 152.5 ± 17.5 kg and 102.5 ± 12.5 kg, respectively. A minimum of three- and six-minutes recovery was provided between sets and each exercise, respectively.

INSERT TABLE 1 NEAR HERE

Kinematic and Kinetic Data Collection

Kinematic data were collected using a 15 camera 3D motion analysis system (Vicon, Oxford Metrics, UK) sampling at 250 Hz. All cameras were calibrated to residual errors of < 0.3 mm using a 240 mm calibration wand. The origin of the capture volume was set consistently across S1-S3, with a right-handed orthogonal global coordinate system of X (medio-lateral), Y (anterior-posterior) and Z (superior). Marker trajectory data were obtained from retroreflective markers (14 mm) attached bilaterally to landmarks consistent with Brazil et al.[28] External force data were collected in S1 using piezoelectric instrumented starting blocks at a sampling rate of 10 000 Hz (post-processed to 1 000 Hz). Force signals from the starting blocks were low pass filtered (4th order Butterworth, 120 Hz cut-off) prior to analysis and were time synchronised with the kinematic data using a known voltage rise prior to the starting sound.[28] During S2 and S3, external force data for each leg were collected independently from two Kistler force platforms (9287BA, Kistler, Switzerland) sampling at 1 000 Hz. External force signals were internally amplified and collected simultaneously with the Kinematic data using Vicon Nexus (v2.2.3), and low pass filtered (4th order Butterworth, 60 Hz cut-off) prior to further analysis.

Data Processing

After labelling of marker trajectories, data corresponding only to the front leg during the block start was subsequently analysed using Visual 3D (v6, C-Motion Inc, Germantown, USA), from a nine-segment model of the lower limb (pelvis and bilateral thigh, shank, foot and toe).[28,29] Raw marker coordinates were low-pass filtered (4th order Butterworth) with a cut-off frequency of 12 Hz (S1) and 8 Hz (S2, S3), respectively, determined using residual analysis.[31] Flexion-extension (x-axis) joint angle data were calculated as the transformation between two segment coordinate systems (SCS) described by an X-Y-Z Cardan sequence of rotations. Positive and negative angles represented extension/ plantarflexion and flexion/ dorsiflexion, respectively. Newton-Euler inverse dynamics procedures were used to calculate front leg flexion-extension resultant joint moments at the ankle ($_{ANK}$), knee ($_{KNE}$) and hip joints ($_{HIP}$) and were resolved in the proximal SCS. Joint power was calculated as the product of joint moment and angular velocity.

For all tasks, a movement phase was defined to provide a valid comparison with the block start (i.e. extension of the front leg in the block start). For the block start and squat variations, movement onset was defined when the first derivative of the resultant or vertical force-time curve, respectively, exceeded 500 N.s.[28] Due to the varying nature of the force-time data for S3, movement onset was defined as the onset of hip extension (angular velocity > 0°.s^{-1}), providing consistency between those performed with and without countermovement. The end of each task was defined by: resultant force < 50 N (block start),[28] local minima in vertical force as the bar approached maximal vertical displacement (BS_{90}) and vertical force < 10 N (all other jump exercises). Magnitudes of front leg average extensor moment (M) and positive extensor power (P) were then quantified at each joint across the movement phase, and normalised as outlined in Brazil et al.[28] Joint angle-, moment- and power-time histories were subsequently normalised to 100% of movement time using a cubic spline.

To quantify intra-limb joint coordination, vector coding techniques were applied to front leg angle-angle plots[32,33] for the hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples, to obtain the coupling angle (CA) at each instance of the normalised phase duration (Fig. 1). For each task, ensemble group average CA profiles for each joint couple were subsequently produced from each individual average CA profile using circular statistics.[32]

INSERT FIGURE 1 NEAR HERE

Data Analysis

Group mean and standard deviations were calculated for joint moment (M) and power (P) using individual mean data from all executed repetitions. To compare magnitudes of joint kinetic data between the block start and each exercise, paired samples t-tests (alpha level P < 0.05) were utilised in conjunction with standardised effect sizes (d), accompanied by 90% confidence intervals to convey the probable range of the true effect. The direction of the effect indicated whether the physical preparation exercise (positive) or block start (negative) was of greater magnitude. When the confidence interval did not overlap zero, effect sizes were interpreted as small ($0.2 \leq d < 0.6$), moderate ($0.6 \leq d < 1.2$), large ($1.2 \leq d < 2.0$), very large ($2.0 \leq d < 4.0$), and extremely large ($d \geq 4.0$).[34] All data were confirmed to be normally distributed (Shapiro-Wilk P > 0.05) prior to analysis.

Coupling angle data were 'binned' into one of eight distinct coordination patterns based on each joint's relative motion (Fig. 1). To quantify overall similarity in joint coordination between the block start and each training exercise, coupling angle difference (CA_{DIF}) was calculated, by computing a 'difference score' in coordination pattern (bin), ranging from 0 (same bin) to 4 (opposite bin) at each instance across the normalised time cycle. The sum of each difference score was then expressed as a percentage of the maximum possible value, with a lower CA_{DIF} representing increased similarity with the competitive motor task.

To support discrete (variables reduced from time-series data) analyses of joint kinetic and intra-limb joint coordination data, qualitative visualisation techniques were also utilised.[35] For joint angle, moment and power data, standardised effect sizes (d) were calculated at each instance across the normalised time cycle and the magnitude of *d* was converted to a specific colour value of red (R), green (G), and blue (B) (Table 2). A modified colour spectrum was used for CA data, with the colour assigned at each instance of the normalised time cycle based on the aforementioned 'difference score' (Table 2).

INSERT TABLE 2 NEAR HERE

RESULTS

Mean ± SD absolute movement durations for each task were 0.370 ± 0.019 s (block start), 0.371 ± 0.073 s (JS_0), 0.659 ± 0.099 s (JS_{60}), 1.171 ± 0.339 s (BS_{90}), 0.330 ± 0.034 s (HJ_{BL}), 0.386 ± 0.022 s (HJ_{SP}), 0.330 ± 0.025 s (MBD_{BL}) and 0.485 ± 0.107 s (MBD_{SP}).

Single Joint Kinematics & Kinetics

At the ankle joint, very large to extremely large differences in joint angle were observed between all exercises and the block start, indicating that the ankle joint was operating within greater dorsiflexion in all exercises compared with the block start (Fig. 2). Aside from JS_0 and BS_{90} (both $P > 0.05$), all exercises exhibited a significantly greater magnitude of M_{ANK} than the block start (d = 1.07 to 4.85, $P < 0.05$), with the largest difference observed for the HJ_{BL} and MBD_{BL} exercises (Table 3). Whilst HJ_{BL} and MBD_{BL} showed consistently larger magnitudes of M_{ANK} than the block start, for JS_{60}, HJ_{SP} and MBD_{SP}, positive differences were most apparent following 50% of movement time (Fig. 2). At the joint power level, aside from, BS_{90}, all other exercises elicited significantly greater P_{ANK} compared with the block start, with JS_0 (d = 2.06, very large), HJ_{SP} (d = 3.76, very large) and HJ_{BL} (d = 4.56, extremely large) showing the largest magnitudes of difference (Table 3).

INSERT TABLE 3 NEAR HERE

At the onset and end of movement, knee joint angle in all training exercises was similar to the block start, with BS_{90} demonstrating the greatest overall similarity (Fig. 2). Significant positive differences in M_{KNE} were only observed for JS_{60} (d = 1.52, large, $P < 0.05$) and BS_{90} (d = 1.61, large, P

< 0.05), with a moderate negative difference found for HJ_{SP} (d = -1.17, P < 0.05) (Table 3). Localised positive differences were observed during the first 50% of movement time, where JS_0, JS_{60} and BS_{90} possessed the largest magnitudes of difference (Fig. 2). Aside from BS_{90} (d = -1.69, large, P < 0.05), all other exercises showed no difference in $P_{KNE,}$ though confidence intervals for JS_0 and all horizontal exercises had upper bounds between moderate and large positive effects (Table 3).

Hip joint angles were similar between all exercises and the block start during the first 40% of movement time, although subsequently remained in a more extended position during the block start (Fig. 2). Average hip extensor moment was smaller in JS_0 (d = -1.47, large, P < 0.05), not different in MBD_{BL} and MBD_{SP}, and greater in JS_{60} (d = 1.75, large, P < 0.05), HJ_{BL} (d = 1.32, large, P < 0.05), HJ_{SP} (d = 1.62, large, P < 0.05), and BS_{90} (d = 2.16, very large, P < 0.05) compared with the block start (Table 3). However, a local period of very large and extremely large positive difference during the first 20% of movement was observed in all exercises, followed by a secondary period in JS_{60} and BS_{90} from 60% onwards (Fig. 2). During the main period of positive hip extensor power, all exercises demonstrated similar or smaller magnitudes compared with the block start (Fig. 2), resulting in no difference in P_{HIP} being observed for HJ_{BL} and HJ_{SP}, with the remaining exercises showing very large to extremely large negative differences (d = -2.16 to -5.51, P < 0.05) (Table 3).

INSERT FIGURE 2 NEAR HERE

Intra-Limb Joint Coordination

Coupling angle difference (CA_{DIF}) for all joint couples are presented in Table 4, with Figure 3 detailing all ensemble average coupling angle profiles. Overall CA_{DIF} was typically higher for the K-A joint couple and lower for the exercises performed from a bilateral stance (Table 4).

INSERT TABLE 4 HERE

For the H-K and K-A joint couples, CA_{DIF} was lower for the squat variations (9-13% and 11-19%, respectively) compared with the horizontal exercises (15-26% and 28-34%, respectively), with MBD_{SP} exhibiting the highest CA_{DIF} in comparison to the block start (Table 4). For the H-A joint couple, similarly low values of CA_{DIF} were observed for most exercises (7-9%), but was again higher for MBD_{SP} (17%) (Table 4). For all joint couples, inter-exercise differences in CA_{DIF} appeared to be determined by disparity in coordination patterns at the onset of movement, until patterns of proximal and in-phase extension emerged throughout all tasks (Fig. 3). In particular, for H-K and K-A couples, the squat variations were found to closer replicate proximal extension and anti-phase coordination patterns emergent in the block start, respectively, across the initial 40% of movement time (Fig. 3).

****INSERT FIGURE 3 HERE****

DISCUSSION

The aim of this study was to investigate the training principles of overload and specificity using joint kinetic and intra-limb joint coordination analyses, to advance biomechanical understanding of the principles of training within exercise section. From the current analyses, all exercises were able to elicit a heightened musculoskeletal demand compared with the block start, although this was dependent on the biomechanical variable of interest. In addition, whilst all exercises promoted proximal and in-phase extension coordination patterns that emerged in the block start, traditionally-viewed more general exercises possessed greater overall coordination similarity, attributed primarily through greater similarity at the onset of movement.

As adaptations to strength training are known to be joint angle specific,[10] when considering joint angle information concomitantly with joint kinetic data, the functionality of musculoskeletal overload with respect to a competitive motor task can be better understood. From a constraints based approach,[27] ensuring a functional level of musculoskeletal overload, targeted towards relevant determinants of competitive task performance, may favourably alter organismic constraints that increase an athlete's motor potential to execute a task to a higher level of performance.

Aside from JS_0 and BS_{90}, all exercises exhibited significantly larger ankle plantarflexor moments compared with the block start (Table 3). As M_{ANK} has been previously associated with external horizontal force during the block start,[29] the observed overload can be considered specific to the biomechanical determinants of this competitive motor task. Typically, the horizontal (S3) exercises elicited their greatest overload as the ankle plantarflexor moment was resisting dorsiflexion (Fig. 2), providing relevant stimulus to improve ankle stiffness and subsequently enhance block performance through; (i) shortening the reversal time between dorsi- and plantar-flexion,[36] (ii) improving force transmission from the hip extensors into the blocks,[37] or (iii) improving horizontal orientation of the resultant force vector.[38] The larger plantarflexor moments compared with the block start may be explained by the increased magnitude of ankle dorsiflexion within each training exercise, altering the force-length properties of the plantarflexor musculature.[39]

All jump exercises increased positive plantarflexor power compared with the block start (Table 3), indicating all could be utilised in the physical preparation of athletes to improve plantarflexor power generation capacity. The efficacy of increased neuromuscular potential of the plantarflexor musculature to be effectively utilised within the block start is however threatened by the lack of correspondence in ankle joint angle.[3] Nonetheless, although increases in strength have been found to be greatest at the angular region promoted in training, residual effects have been documented outside of the trained range of motion.[40] Determining the bandwidth to which adaptations are angle-specific during dynamic tasks would be an insightful avenue for future investigation.

Knee and hip joint extensor moments are determining characteristics of block start horizontal force production and overall performance.[29] In this study, only JS_{60} and BS_{90} exhibited significantly higher M_{KNE} compared with the block start, and the greatest difference in M_{HIP} was observed for BS_{90} (Table 3). Furthermore, the squat variations (S2) showed very large to extremely large positive differences in knee and hip extensor moments at the beginning of movement, when joint angles were similar to the block start (Fig. 2). Externally loaded squat-based exercises can therefore be considered to specifically overload the extensor moment demand of the knee and hip joints for the block start. The capability of BS_{90} to elicit relevant musculoskeletal overload in relation to the block start, may offer some biomechanical explanation for why increased maximal squat strength has been found to increase sprint acceleration performance,[41] and helps to justify the implementation of near maximal loads within physical preparation for sprinters.[26] Whilst BS_{90} elicited the greatest hip extensor moment overload, all exercises showed large to extremely large increases at the beginning of movement (Fig. 2). The importance of waveform data analysis was therefore recognised, and suggested that similar local overload could be achieved under a range of task constraints, such as near maximal external loads (BS_{90}) or a preceding countermovement (HJ). Practitioners should therefore consider that perceived overload (i.e. increasing external resistance) may not correspond with musculoskeletal overload, stressing the importance of embedding biomechanical analysis within exercise selection.

Apart from BS_{90}, all exercises appeared to replicate the musculoskeletal demand to generate knee extensor power in the block start (Fig. 2). The range of confidence intervals for P_{KNE} (Table 3) suggested that the magnitude of overload was athlete-specific, supporting that individual strategies can emerge when performing the same task,[42] which may influence optimal training practices. At the hip joint, no exercise overloaded the extensor power generating characteristics of the block start (Table 3, Fig. 2). Whilst improvements in hip extensor power could occur as a consequence of increasing strength,[43] further research is required to identify those exercises capable of overloading the extensor power generating capacity of the hip extensors compared with the block start. Olympic lifts may offer an interesting avenue for future research in this area, given their large demand on hip extensor power generation.[44]

Ensuring similarity in coordinative patterns between training and competitive motor tasks (movement specificity), may enable changes in organismic constraints to be effectively utilised in the competitive task by promoting the emergence of task specific coordinative structures.[18,19] By adopting vector coding analyses, the current study aligned the intrinsic dynamics of each task as a mechanism to identify those exercises with the greatest potential to enhance skill performance.[18] Results questioned modern exercise categorisation on a spectrum of specificity based on perceived kinematic replication of a competitive motor task,[23-25] as traditionally viewed less specific exercises (JS_0, JS_{60}, BS_{90}) often exhibited greater coordination similarity with the block start (Table 4). In addition, adopting a split stance during HJ and MBD to enhance perceived similarity of block start postures, resulted in a reduced ability to replicate lower limb coordination patterns (Table 4).

Results highlighted that the appearance of an exercise does not necessarily dictate the interaction between working joints in a multi-linked system and adopting an intra-limb coordinative approach to quantify movement specificity is encouraged.[18-20] Although CA_{DIF} was generally higher for the horizontal exercises, all were able to replicate dominant proximal and in-phase extension coordination patterns emergent in the block start (Fig. 3). Therefore, although inherently different in appearance, all exercises were found to promote the self-organisation of coordinative structures functionally linked with competitive task execution. Inter-exercise differences in coordination patterns were consistently observed at the beginning of movement, and was the main contributing factor to inter-exercise differences in CA_{DIF} (Table 4, Fig. 3). Different task constraints,[27] as well as different state changes at movement onset,[45] likely dictated the initial differences in coordination patterns.

In practice, the scientific bases of specific adaptations to imposed stress[3] are often interpreted to determine an exercises level of 'specificity' based on kinematic (movement patterns and velocity) replication of the competitive motor task.[23-25] The current investigation challenged this view and encouraged a reconceptualisation of the principle of specificity within exercise selection. For example, BS_{90} exhibited joint angle specific extensor moment overload of the front leg knee and hip joints, whilst replicating competition task specific coordination patterns. Whilst traditionally this exercise would be classed as a 'general' or 'non-specific' training method for sprinting,[2,22,25] results indicated that BS_{90} provides a coordinative specific means of improving key biomechanical determinants of performance (front leg knee & hip extensor strength). By embedding the principles of training within the framework of coordinative dynamics and self-organisation,[27] exercise selection should consider both the desired change in organismic constraints related to the biomechanical determinants of performance and the promotion of task-specific coordinative structures, so that altered organismic constraints have the best chance of being effectively utilised in the competitive motor task. Overload and specificity would therefore be synergistic, dictating the nature of biological adaptation that influence the interaction between an organism and the task. The results of this study highlight the need for comprehensive, holistic approaches to investigate the principles of overload and specificity within exercise selection, to afford practitioners an evidence base when selecting physical preparation exercises to enhance athletic performance.

A novel aspect to this research was the complimentary nature of discrete and waveform analyses in relation to the principles of overload and specificity, aiding the visualisation of local differences[35] to evaluate training exercises. In addition, CA_{DIF} offered a unique method to quantify overall differences between vector coding profiles, extending beyond qualitative inferences or frequency analysis of binned coordination patterns.[32] A limitation of the current study for its application to the block start is that only the front leg was examined. However, the wider scope of the study was to present a biomechanical approach (combined joint kinetic and intra-limb coordination analyses) to examine overload and specificity characteristics of training exercises that can be applied to any sporting task. Whilst biomechanical analysis can provide insight into the potential adaptations and mechanisms to improve sports performance, the outcome remains unknown. Future research should therefore endeavour to identify the nature of biological adaptation and its effect on joint kinetic and coordinative strategies when executing a competitive motor task.

The current study has contributed to advanced understanding of the principles of overload and specificity within exercise selection, by: (i) demonstrating that both traditionally viewed general and more specific exercises were able to elicit joint kinetic overload targeting different biomechanical determinants of performance, and (ii) showing that all exercises promoted the emergence of proximal and in-phase extension joint coordination patterns linked with block start execution, although traditionally viewed less-specific exercises possessed greatest overall similarity. By integrating traditional theories of training and contemporary exercise classification with the constraints based approach to human movement, the current research encouraged a reconceptualisation of what constitutes a 'sport specific' training exercise, and can influence how scientists, coaches and athletes utilise biomechanical processes to enable objective decisions regarding exercise selection to enhance human performance.

DISCLOSURE OF INTEREST

The authors report no conflict of interest .

REFERENCES

1. Bolger R, Lyons M, Harrison AJ, Kenny IC. Coaching sprinting: Expert coaches' perception of resistance-based training. *Int J Sports Sci Coach.* 2016;11:746-754.
2. Burnie L, Barratt P, Davids K, Stone J, Worsfold P, Wheat J. Coaches' philosophies on the transfer of strength training to elite sports performance. *Int J Sports Sci Coach.* 2018;13:729-736.
3. Siff MC. Supertraining. 6th ed. Denver: Supertraining International; 2003.
4. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med*. 2016;46:1419-1449.
5. Zatsiorsky, V. M, & Kraemer, WJ. Science and practice of strength training, 2nd ed.. Champaign, IL: Human Kinetics; 2006.
6. Stone, MH, & Stone, ME. Resistance training modes: A practical perspective. In: Cardinale, M, Newton, R, & Nosaka, K, editors. Strength and conditioning: biological principles and practical applications. West Sussex, UK: Wiley-Blackwell; 2011. P. 345-357.
7. Kawamori N, Newton RU, Hori N, Nosaka K. Effects of weighted sled towing with heavy versus light load on sprint acceleration ability. J Strength Cond Res. 2014;28:2738-2745.
8. Okkonen O, Häkkinen K. Biomechanical comparison between sprint start, sled pulling, and selected squat-type exercises. J Strength Cond Res. 2013;27:2662-2673.
9. Young WB. Transfer of strength and power training to sports performance. *Int J Sports Physiol Perform*. 2006;1:74-83.
10. Morrissey MC, Harman EA, Johnson MJ. Resistance training modes: specificity and effectiveness. *Med Sci Sports Exerc*. 1995;27:648-660.
11. Irwin G, Hanton S, Kerwin DG. The conceptual process of skill progression development in artistic gymnastics. *J Sports Sci*. 2005;23:1089-1099.
12. Swinton PA, Stewart AD, Lloyd R, Agouris I, Keogh JW. Effect of load positioning on the kinematics and kinetics of weighted vertical jumps. *J Strength Cond Res*. 2012;26:906-913.
13. Swinton PA, Stewart A, Agouris I, Keogh JW, Lloyd R. A biomechanical analysis of straight and hexagonal barbell deadlifts using submaximal loads. *J Strength Cond Res*. 2011;25:2000-2009.
14. Farris DJ, Lichtwark GA, Brown NA, Cresswell AG. Deconstructing the power resistance relationship for squats: A joint-level analysis. *Scand J Med Sci Sports*. 2016;26:774-781.

15. Mero A, Komi PV. EMG, force, and power analysis of sprint-specific strength exercises. *J Appl Biomech*. 1994;10:1-13.
16. Wilson GJ, Murphy AJ, Walshe A. The specificity of strength training: the effect of posture. *Eur J Appl Physiol Occup Physiol*. 1996;73:346-352.
17. Sparrow WA, Donovan E, Van Emmerik R, Barry EB. Using relative motion plots to measure changes in intra-limb and inter-limb coordination. *J Mot Behav*. 1987;19:115-129.
18. Irwin G, Kerwin DG. Inter-segmental coordination in progressions for the longswing on high bar. *Sports Biomech*. 2007;6:131-144.
19. Wilson C, Simpson S, Hamill J. Movement coordination patterns in triple jump training drills. *J Sports Sci*. 2009;27:277-282.
20. Romanazzi M, Galante D, Sforza C. Intralimb joint coordination of the lower extremities in resistance training exercises. *J Electromyogr Kinesiol*. 2015;25:61-68.
21. Bolger R, Lyons M, Harrison AJ, Kenny IC. Sprinting performance and resistance-based training interventions: a systematic review. *J Strength Cond Res*. 2015;29:1146-1156.
22. Rumpf MC, Lockie RG, Cronin JB, Jalilvand F. Effect of different sprint training methods on sprint performance over various distances: A brief review. *J Strength Cond Res*. 2016;30:1767-1785.
23. Young W, Benton D, John Pryor M. Resistance training for short sprints and maximum-speed sprints. *Strength Cond J*. 2001;23:7-13.
24. Sheppard JM. Strength and conditioning exercise selection in speed development. *Strength Cond J*. 2003;25:26-30.
25. Wild J, Bezodis NE, Blagrove R, Bezodis I. A biomechanical comparison of accelerative and maximum velocity sprinting: specific strength training considerations. *Prof Strength Cond*. 2011;21:23-37.
26. Moir GL, Brimmer SM, Snyder BW, Connaboy C, Lamont HS. Mechanical limitations to sprinting and biomechanical solutions: a constraints-led framework for the incorporation of resistance training to develop sprinting speed. *Strength Cond J*. 2018;40:47-67.
27. Newell K. Constraints on the development of coordination. In Wade MG, Whiting HTA, editors. Motor development in children: aspects of coordination and control. Dordrecht: Martinus Nijhoff; 1986. 341-360 p.

28. Brazil A, Exell T, Wilson C, Willwacher S, Bezodis I, Irwin G. Lower limb joint kinetics in the starting blocks and first stance in athletic sprinting. *J Sports Sci*. 2017;35:1629-1635.
29. Brazil A, Exell T, Wilson C, Willwacher S, Bezodis I, Irwin G. Joint kinetic determinants of starting block performance in athletic sprinting. *J Sports Sci*. 2018;36:1656-1662.
30. Willwacher S, Herrmann V, Heinrich K, Funken J, Strutzenberger G, Goldmann JP, et al. Sprint start kinetics of amputee and non-amputee sprinters. PloS One. 2016;11:e0166219.
31. Winter DA. Biomechanics and motor control of human movement. 4th ed. Hoboken: John Wiley and Sons, Inc; 2009.
32. Chang R, Van Emmerik R, Hamill J. Quantifying rearfoot–forefoot coordination in human walking. *J Biomech*. 2008;41:3101-3105.
33. Needham R, Naemi R, Chockalingam N. Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique. Journal of Biomechanics. 2014;47:1020-1026.
34. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41:3-12.
35. Manal K, Stanhope SJ. A novel method for displaying gait and clinical movement analysis data. *Gait Posture*. 2004;20:222-226.
36. Guissard N, Duchateau J, Hainaut K. EMG and mechanical changes during sprint starts at different front block obliquities. *Med Sci Sports Exerc*. 1992;24:1257-1263.
37. Cavagna GA. Storage and utilization of elastic energy in skeletal muscle. *Exerc Sport Sci Rev*. 1977;5:89-130.
38. Rabita G, Dorel S, Slawinski J, Sàez-de-Villarreal E, Couturier A, Samozino P, Morin JB. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scand J Med Sci Sports*. 2015;25:583-594.
39. Sale D, Quinlan J, Marsh E, McComas AJ, Belanger AY. Influence of joint position on ankle plantarflexion in humans. *J Appl Physiol*. 1982;52:1636-1642.
40. Graves JE, Pollock ML, Jones AE, Colvin AB, Leggett SH. Specificity of limited range of motion variable resistance training. *Med Sci Sports Exerc*. 1989;21:84-89.
41. Seitz LB, Reyes A, Tran TT, de Villarreal ES, Haff GG. Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports Med*. 2014;44): 1693-1702.

42. Bradshaw EJ, Maulder PS, Keogh JW. Biological movement variability during the sprint start: Performance enhancement or hindrance? *Sports Biomech*. 2007;6:246-260.

43. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: biological basis for maximal power production. *Sports Med*. 2011;41:17-38.

44. Kipp K, Malloy PJ, Smith JC, Giordanelli MD, Kiely MT, Geiser CF, Suchomel TJ. Mechanical demands of the hang power clean and jump shrug: A joint-level perspective. *J Strength Cond Res*. 2018;32:466-474.

45. Heiderscheit BC, Hamill J, van Emmerik RE. Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *J Appl Biomech*. 2002;18:110-121.

Table 1. Details of the physical preparation exercises within the current study. In accordance with contemporary practice, the level of specificity increases in descending order.

Exercise Name	Exercise Description
Concentric only Back Squat with 90% 1RM external load (BS_{90})	With a barbell loaded to 90% 1RM placed across the shoulders, the athlete descends until the bar settles on safety blocks, corresponding to approximately 90° knee flexion. From this stationary starting position, the athlete aims to stand with the intent of moving as fast as possible.
Concentric only Jump Squat (high-load, 60% 1RM) (JS_{60})	With a barbell loaded to 60% 1RM placed across the shoulders, the athlete descends until the bar settles on safety blocks, corresponding to approximately 90° knee flexion. From this stationary starting position, the athlete explosively jumps into the air to maximise jump height **60% and 90% relative loads were based on assessment of 1RM concentric only back squat within one week of S2 data collection.*
Concentric only Jump Squat (low-load) (JS_0)	With a barbell and 2.5kg bumper plates (25 kg) placed across the shoulders, the athlete descends until the bar settles on safety blocks, corresponding to approximately 90° knee flexion. From this stationary starting position, the athlete explosively jumps into the air to maximise jump height.
Bilateral Horizontal Jump (HJ_{BL})	From a normal standing position, the athlete performs a horizontal jump with countermovement, with the objective of projecting as far as possible in the horizontal direction
Bilateral Medicine Ball Dive (MBD_{BL})	The athlete adopts a crouched position with a 5 kg medicine ball close to the chest. Then, the athlete explosively dives forwards whilst throwing the medicine ball in the horizontal direction. For safety, the athlete dives onto a crashmat following the release of the medicine ball.
Split Stance Horizontal Jump (HJ_{SP})	Same as HJ_{BL} but adopting a split stance position (one foot in front of the other to emulate the nature of the block start). Each athlete positioned their front and rear leg to match that of their block start setup.
Split Stance Medicine Ball Dive (MBD_{SP})	Same as MBD_{BL} but adopting the split stance position, matching the front and rear foot setup in the block start.

Table 2. Contributions of red (R), green (G) and blue (B) for values of *d* (top) and representative differences in coordination patterns (bottom). The direction of *d* indicates whether the block start (negative) or exercise (positive) was of greater magnitude.

d	Interpretation	R	G	B	Colour
$d < -4.0$	Extremely large negative difference	255	0	0	
$-2.0 \geq d > -4.0$	Very large negative difference	255	128	0	
$-1.2 \geq d > -2.0$	Large negative difference	255	255	0	
$-0.6 \geq d > -1.2$	Moderate negative difference	128	255	0	
$-0.6 < d < 0.6$	Not different	0	255	0	
$0.6 \leq d < 1.2$	Moderate positive difference	0	255	128	
$1.2 \leq d < 2.0$	Large positive difference	0	255	255	
$2.0 \leq d < 4.0$	Very Large positive difference	0	128	255	
$d > 4.0$	Extremely large positive difference	0	0	255	

Coordination Difference Score	Interpretation	R	G	B	Colour
0	Same bin	0	255	0	
1	Neighbouring bin	128	255	0	
2	Two bins difference	255	255	0	
3	Three bins difference	255	128	0	
4	four bins difference	255	0	0	

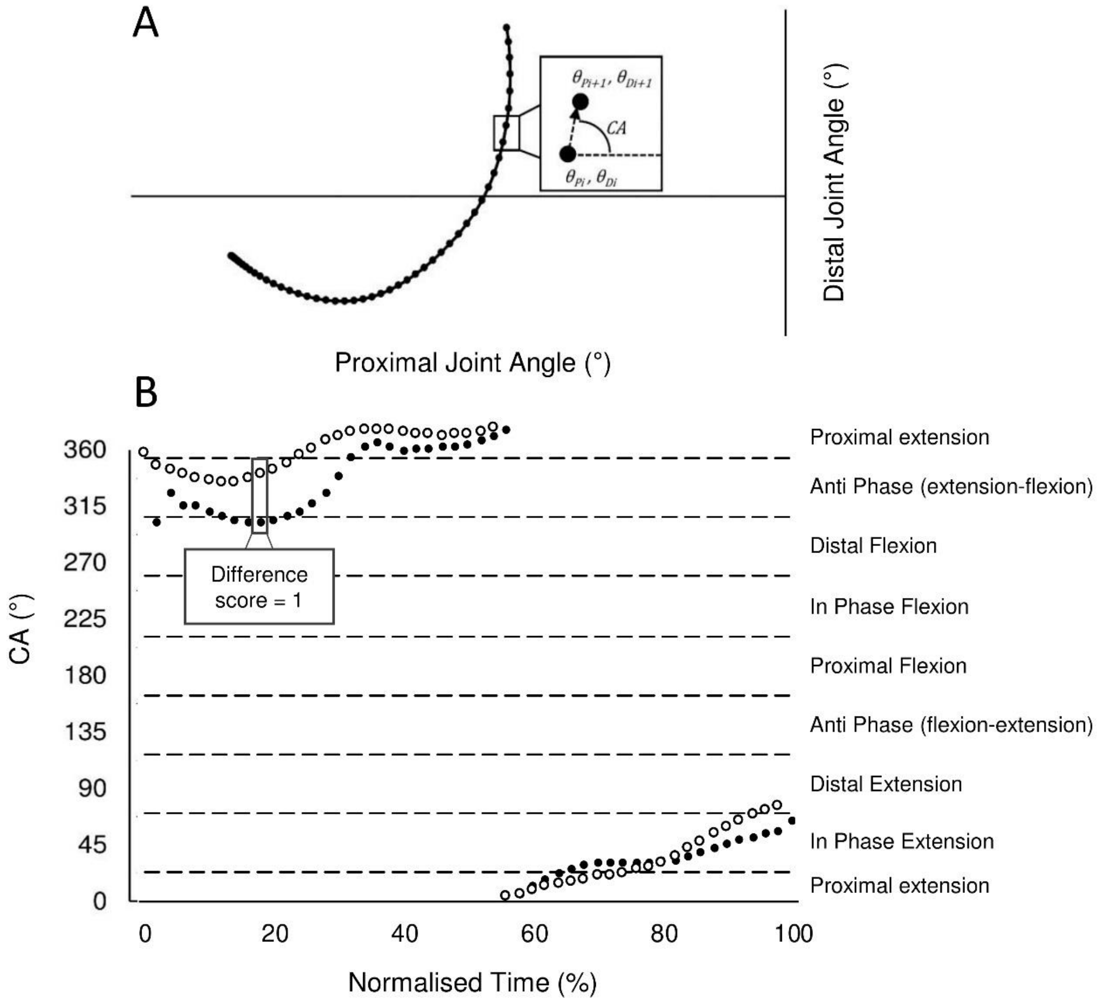
Table 3. Group mean ± standard deviation average extensor joint moment (M) and positive extensor joint power (P). Standardised effect size (*d*) and 90% confidence intervals (CI) between the block start and each exercise are shown.

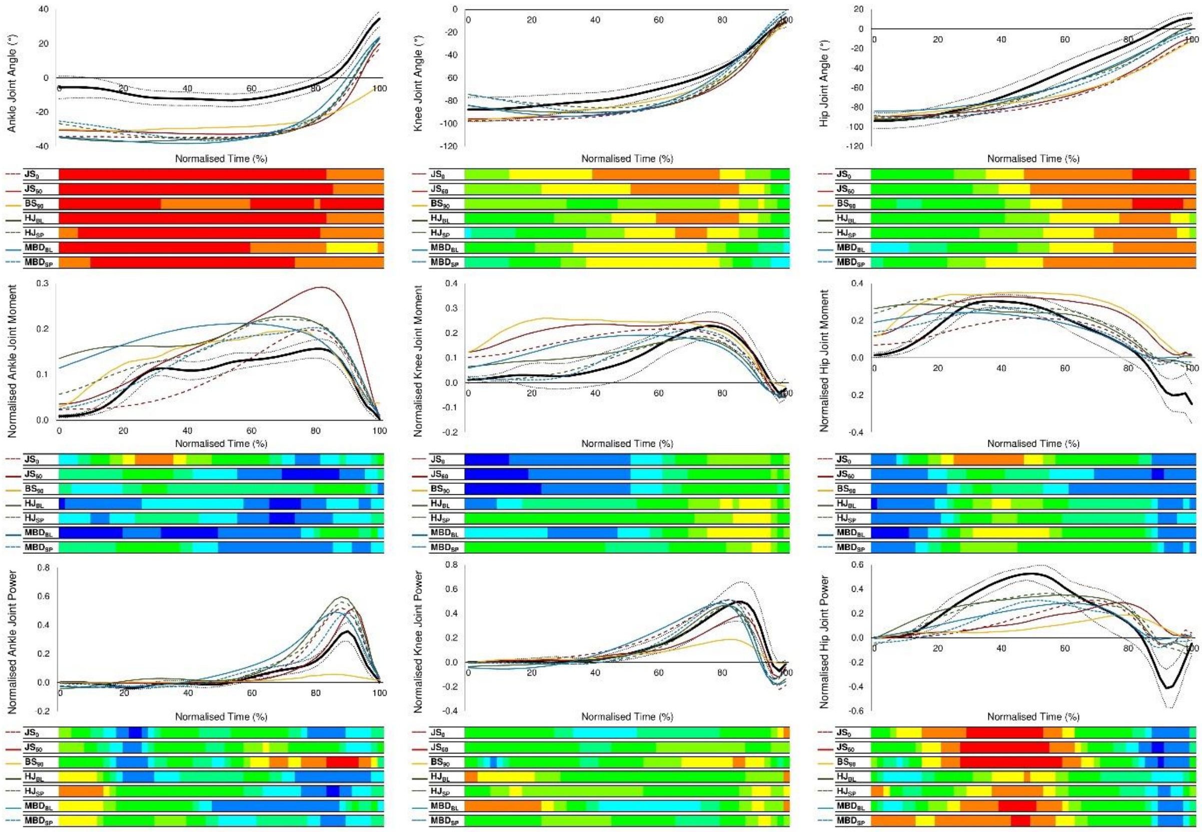
	M_{ANK}							M_{KNE}							M_{HIP}						
Exercise	mean		SD	*d*	CI-	CI+		mean		SD	*d*	CI-	CI+		mean		SD	*d*	CI-	CI+	
Block Start	0.096	±	0.010					0.135	±	0.045					0.186	±	0.029				
JS_{0}	0.093	±	0.020	-0.16	-1.18	0.85	ND	0.163	±	0.009	0.72	-0.36	1.81	ND	0.146	±	0.014*	-1.47	-2.42	-0.52	L
JS_{60}	0.161	±	0.028*	2.58	1.71	3.45	VL	0.204	±	0.030*	1.52	0.41	2.63	L	0.244	±	0.027*	1.75	0.89	2.60	L
BS_{90}	0.140	±	0.047	1.07	0.20	1.94	M	0.217	±	0.040*	1.61	0.50	2.73	L	0.279	±	0.043*	2.16	1.44	2.89	VL
HJ_{BL}	0.180	±	0.023*	3.95	3.02	4.87	VL	0.117	±	0.027	-0.40	-1.20	0.41	ND	0.229	±	0.026*	1.32	0.38	2.25	L
HJ_{SP}	0.142	±	0.017*	2.73	2.15	3.31	VL	0.086	±	0.020*	-1.17	-1.91	-0.43	M	0.247	±	0.035*	1.62	0.76	2.48	L
MBD_{BL}	0.166	±	0.014*	4.85	3.79	5.90	EL	0.142	±	0.024	0.16	-0.82	1.13	ND	0.181	±	0.018	-0.16	-1.09	0.77	ND
MBD_{SP}	0.123	±	0.018*	1.53	0.73	2.32	L	0.100	±	0.024	-0.82	-1.51	-0.13	M	0.185	±	0.027	-0.04	-0.59	0.52	ND
	P_{ANK}							P_{KNE}							P_{HIP}						
Block Start	0.130	±	0.027					0.202	±	0.077					0.285	±	0.041				
JS_{0}	0.187	±	0.019*	2.06	1.30	2.81	VL	0.185	±	0.029	-0.25	-1.32	0.82	ND	0.145	±	0.012*	-3.93	-4.80	-3.07	VL
JS_{60}	0.176	±	0.034*	1.26	0.82	1.70	L	0.134	±	0.025	-1.00	-2.11	0.11	ND	0.132	±	0.010*	-4.34	-5.37	-3.31	EL
BS_{90}	0.033	±	0.010*	-4.06	-4.86	-3.27	EL	0.087	±	0.024*	-1.69	-2.78	-0.61	L	0.091	±	0.010*	-5.51	-6.57	-4.45	EL
HJ_{BL}	0.285	±	0.030*	4.56	3.62	5.50	EL	0.225	±	0.047	0.31	-0.76	1.38	ND	0.257	±	0.057	-0.47	-1.20	0.26	ND
HJ_{SP}	0.235	±	0.019*	3.76	3.23	4.30	VL	0.222	±	0.026	0.30	-0.46	1.06	ND	0.254	±	0.032	-0.72	-1.61	0.17	ND
MBD_{BL}	0.208	±	0.047*	1.71	0.58	2.84	L	0.258	±	0.039	0.78	-0.30	1.86	ND	0.165	±	0.023*	-3.05	-3.89	-2.20	VL
MBD_{SP}	0.187	±	0.026*	1.80	0.63	2.96	L	0.259	±	0.035	0.80	-0.18	1.78	ND	0.195	±	0.029*	-2.16	-2.45	-1.86	VL

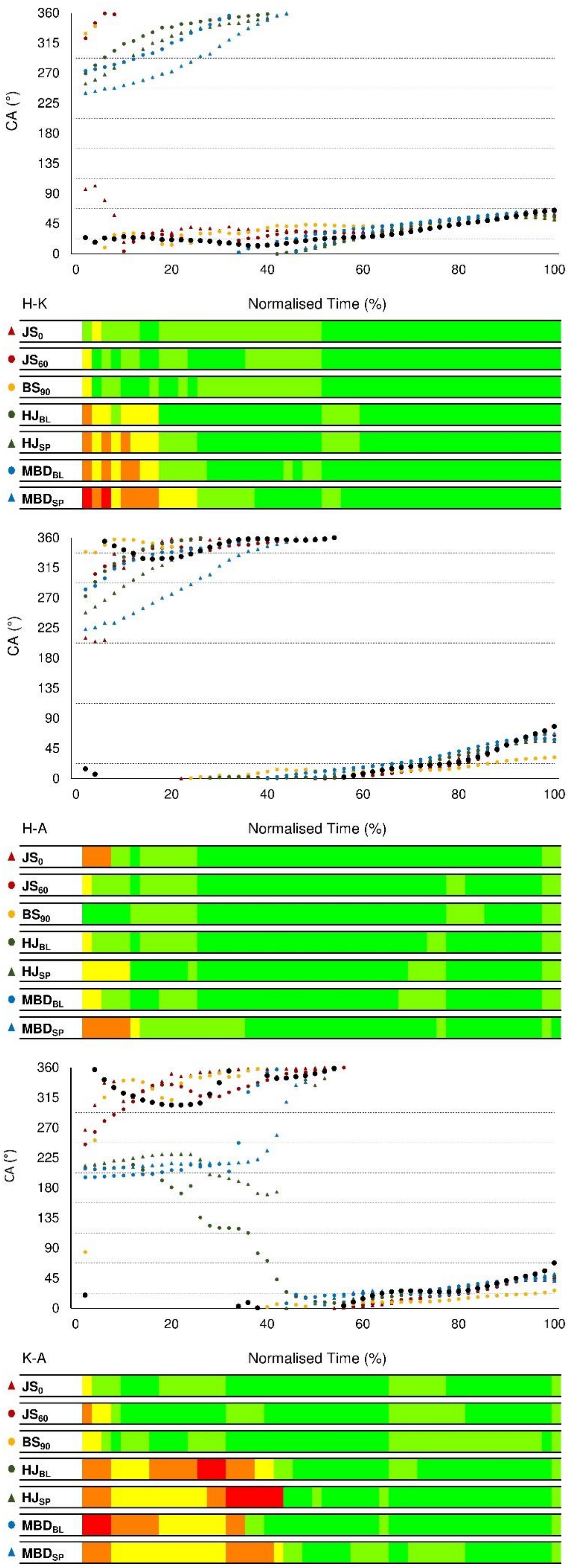
** denotes P < 0.05. Superscript label denotes no difference (ND) or the interpretation of d; moderate (M), large (L), very large (VL) extremely large (EL).*

Table 4. Group mean (and individual range) coupling angle difference (CA_{DIF}) between the block start and each exercise, for the hip-knee (H-K), hip-ankle (H-A) and knee-ankle (K-A) joint couples.

	H-K (%)		H-A (%)		K-A (%)	
Exercise	mean	(range)	mean	(range)	mean	(range)
JS_0	13	(9 - 22)	7	(3 - 12)	11	(5 - 19)
JS_{60}	10	(7 - 13)	7	(4 - 9)	13	(11 - 17)
BS_{90}	9	(2 - 13)	9	(5 - 14)	19	(15 - 22)
HJ_{BL}	15	(9 - 27)	9	(7 - 12)	29	(24 - 37)
HJ_{SP}	17	(12 -24)	7	(5 - 11)	29	(24 - 42)
MBD_{BL}	17	(13 - 20)	7	(3 - 13)	28	(19 - 45)
MBD_{SP}	26	(21 - 30)	17	(15 - 21)	34	(27 - 43)


A
$\theta_{Pi+1}, \theta_{Di+1}$
CA
θ_{Pi}, θ_{Di}
Distal Joint Angle (°)
Proximal Joint Angle (°)
B
360
315
270
225
180
135
90
45
0
CA (°)
Difference score = 1
Proximal extension
Anti Phase (extension-flexion)
Distal Flexion
In Phase Flexion
Proximal Flexion
Anti Phase (flexion-extension)
Distal Extension
In Phase Extension
Proximal extension
0
20
40
60
80
100
Normalised Time (%)





CA (°)
360
315
270
225
180
135
90
45
0
0
20
40
60
80
100
Normalised Time (%)
H-K
JS0
JS60
BS90
HJBL
HJSP
MBDBL
MBDSP
H-A
K-A

Figure 1. Definition of the coupling angle from angle-angle plots (A), classification of CA data into distinct coordination patterns (B) and example calculation of the 'difference score' based on two CA profiles (B).

Figure 2. Ensemble group average joint angle (top), moment (middle) and power (top) normalised time histories for the block start (black solid line) and each exercise. Data are presented for the ankle (left), knee (middle) and hip (right) joint. Black dotted line represents block start standard deviation. Colour maps visually represent the standardised effect size difference (*d*) between the block start and each exercise (Table 2).

Figure 3. Ensemble group average hip-knee (H-K, top), hip-ankle (H-A, middle) and knee-ankle (K-A, bottom) coupling angle-normalised time histories for the block start (black circles) and each exercise. Colour maps visually represent the 'difference score' in coordination classification with respect to the block start (Table 2).