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Lower Limb Acceleration During the Block-Start vs. Selected Power and Strength Exercises

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LOWER LIMB ACCELERATION DURING THE BLOCK-START VS. SELECTED POWER AND STRENGTH EXERCISES

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THESIS ACCEPTANCE STATEMENT

On behalf of the Graduate Committee for Thomas A. Ordelt I affirm that this manuscript is the final and accepted thesis. Signatures of all committee members are on file with the Graduate School at the University of Maine, 5755 Stodder Hall, Room 42, Orono, Maine 04469.

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An Abstract of the Thesis Presented
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The purpose of this study was to determine the effect of load changes on angular accelerations of the ankle, knee and hip joints. Accelerations were measured in the squat (S), power clean (PC) and power hang clean (PHC), and compared to the accelerations in the push-off phase of the sprint start (SS). **Methods:** Nine female Division I college track athletes performed block sprint-starts, single-leg squat jumps (1S0) with 0% of 1RM, squats (jump) with 0, 25, 40% of 1RM, and PC and PHC with 30, 50, 75, 100% of 1RM. The fastest trial of each exercise was analyzed for minimum and maximum angular accelerations. A one-way, repeated measures ANOVA was used to determine any main effect among the variables between the exercises. Established effects were identified further using Least Square Difference post-hoc analysis. **Results:** Overall, angular accelerations differed mainly between groups of exercises (S vs. PC vs. PHC), less so within the groups ($p < 0.05$). Only for minimum angular knee joint acceleration in PHC and for minimum angular hip joint acceleration in S was change in acceleration significantly related to change in load. The ankle, knee and hip joint angular acceleration values in S, particularly the low-load S0, 1S0 and S25, were similar to the values measured in the SS. PC and PHC generally had smaller acceleration peaks, yet maximum angular knee and hip joint accelerations of all PCs and of PHC with 30% of 1RM approached the values of SS and S. **Conclusion:** Results suggest that light-load squat jumps emulate lower limb angular accelerations of the push-off phase in the sprint start much closer than medium- or heavy-load squats, or power cleans or power hang cleans. The lack of load dependency in PC and PHC should be studied further with athletes skilled in Olympic lifts.

Key Words: sprint start, block start, angular acceleration, power clean, hang clean, squat

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INTRODUCTION

Training programs for track athletes are designed to improve their speed. Particularly for sprinters, this training traditionally includes a multitude of weightlifting exercises designed to increase muscular force (strength), and field exercises (jumps and bounds) to increase the speed at which that force can be applied (power).

Numerous studies have researched the kinetic and /or kinematic parameters of the different phases in sprinting as well as those of various strength and power exercises. [12,17,20,24,27-31,40,48,49,53,56,62,66-68,72,73,75,79-81,90-95,101,102,106-111,113-116,118,129,131,132,142]

Harland & Steele provided a comprehensive review dealing solely with the biomechanics of the sprint start.[55] Čoh determined the correlation of various kinetic parameters in female national level sprinters to their 20 m time: maximum absolute horizontal force in the blocks ($r = -0.83$) and maximum relative horizontal force in the blocks ($r = -0.85$); maximum rate of force development (RFD) ($r = -0.78$); maximum force impulse ($r = -0.71$) and time to maximum force ($r = 0.69$).[27] A recent study confirmed the importance of high RFD and high force impulse for achieving superior block phase outcome measures.[131]

Similarly, the kinetics and kinematics of strength and power exercises such as the squat,[10,32,33,34,38,39,41,57,70,78,87,98,121,126,127,148] the clean,[21,42,43,51,74,76,77,84,134] the snatch,[7,26,46,47,64,69,82,83,125,135,146] various jumps,[4,11,15,16,44,52,85,89,105,119,128,138,139,140,141,147] and their many variations (e.g. power clean, hang clean, drop jump, squat jump, countermovement jump) have been researched extensively. For instance, Garhammer & Gregor investigated the snatch and the countermovement vertical jump (CMVJ) at different levels of intensity in Olympic level athletes.[44] They concluded that in both exercises the duration of force application at higher percentages of maximum and the rate of force development are at least as important as the magnitude of ground reaction force. Other research supports this finding.[74,76] Arabatzi & Kellis established similar vertical ground reaction forces and similar hip, knee, and ankle angular displacements and velocities in the snatch and the CMVJ.[2]

Another set of studies has looked at the correlations between measures of strength (e.g. one repetition maximum)[1,25,37,35] or power (e.g. horizontal jump distance)[19,25,58,60,63,65,86,99,97,104,133,136] and measures of speed (e.g. 10 m sprint time). Cronin et al. reviewed 18 longitudinal studies on changes of running speed with changes in strength.[35] They found a dearth of research with highly trained athletes. For recreationally trained athletes, they concluded that about 23% increase in squat 1RM was necessary for a significant decrease (> 2%) in sprint times. Correlations between short-distance sprint times and squat 1RM have been reported in the range of r = -0.45 to -0.6.[65,97] In contrast, correlations between short-distance sprint times and various jumps ranged from r = -0.55 to -0.80.[25,63,104]

Other studies have been concerned with the effect of different training methods on various strength, power or speed measures (e.g. 1RM squat, countermovement jump height, standing long jump distance, 30m sprint time). The effects of 8 to 10 weeks of training with high load (low velocity) vs. low load (high velocity), or vs. combined programs, plyometrics, loads selected for maximum power output, or vs. sprint training alone have been investigated.[3,14,36,50,59,61,100,103,117,122,124,144] Unless programs focusing on high loads are accompanied by concurrent high velocity training, programs utilizing high movement velocities appear to be superior in improving sprint times and measures of power output.[3,14]

Many kinetic, kinematic and neuromuscular (EMG) aspects of sprint running and of strength and power exercises have been researched. Little has been done, however, to directly compare the kinetics and kinematics of strength and power exercises to that of sprinting. In fact, only one such study by Mero & Komi compared force, power output, EMG, and various stride variables of maximal velocity sprinting with bounding, stepping, and single-leg hopping performed at maximal velocity. They found maximal bounding to be similar to maximal sprinting in contact time, EMG, force production and force direction. Maximal bounding could thus be used to train sprint-specific neuromuscular patterns. Maximal stepping and hopping had significant differences in many measured parameters to maximal sprinting. The authors recommended gearing such exercises more towards strengthening of the eccentric and concentric activity of hip and knee extensor muscles.[112]

In the block phase of the sprint start, the magnitude of horizontal force generated appears to be more important than the duration of force application.[27,116,132] This means, with mass being constant, the magnitude of acceleration may be a well-correlated measure for the success of a sprint start.[12]

The present paper is based on a larger biomechanical study comparing sprint start and various strength and power exercises in college track athletes and focuses on the acceleration of select body landmarks.

Purpose

The purpose of this study was to determine the acceleration patterns of the hip, knee and ankle joints during the sprint start, and compare them to those of the squat, the power clean and the power hang clean performed with various loads. It was hypothesized that increases in load would cause significant changes in the acceleration patterns, and thus significant differences from the sprint start.

Methods

Data were obtained from 9 female NCAA Division I track athletes. Their competitive events included: sprints up to 400 m, hurdles, long jump and triple jump. The subjects ranged in age from 18 to 20 years and were free from injury. Their physical profile is presented in Table 1. The primary investigator explained the testing procedures and associated risks and benefits of this study to all subjects. All participants signed an informed consent form approved by the University of Maine's institutional review board.

Table 1 Subjects profile.

	Min.	Max.	Mean	SD
Age [yr]	18	20	18.7	0.9
Body Height [m]	1.565	1.760	1.670	0.056
Body Weight [kg]	52.7	70.9	60.3	5.6
Body Fat [%]	12	24	19.1	4.1
Lean Body Weight [kg]	43.6	55.0	48.6	4.1

Instrumentation

All testing was conducted in the University's biomechanical laboratory. An optical motion capture system (Vicon Nexus) with 8 infrared cameras was used to track and calculate the trajectories of 41 full-body and 5 bar retro-reflective passive markers (diameter 14 mm). Cameras were calibrated at least once per day prior to the first session in accordance with the manufacturer's instructions. The capture volume was 6m x 3m x 3m about an indoor track / lifting platform. The full-body model chosen was a standard model used for gait analysis (Plug-in-Gait). In addition to the markers required by this model one extra "tip toe" marker was added over the second distal phalanx. The procedure for identifying and measuring body landmarks as described in the motion capture system manufacturer's user manual was followed.[137] Sampling frequency for the cameras was set at 250Hz.

Standard lab equipment was used for the collection of anthropometric data. Body height and weight were determined in accordance with the Anthropometric Standardization Reference Manual.[88] Specific limb length and joint thickness measurements needed for the gait model were taken with a plastic tape measure and anthropometer.

A Lange skinfold caliper was used for measurement of skinfold thickness in accordance with Beam & Adams[9] and Pollock, Schmidt & Jackson[120]. The Siri equation[130] was used to calculate body fat percentage.

To ensure that the same knee joint angle (90°) was achieved by all the subjects in the squat exercise, an elastic band stretched between the lifting rack posts was employed as a "down" marker. A goniometer was used to measure the knee joint angle as the elastic band was adjusted for correct height and distance to the subject's heels.

Subject Preparation

All anthropometric measures were taken with the subjects dressed in compression shorts and sports bras. In an athlete’s first testing session, body weight, height and skinfold measurements were taken. Anthropometric measurements as required by the motion capture system body model were determined. Marker locations were identified at the beginning of each testing session and marked with permanent marker. Markers were attached with medical-grade double-sided tape. The same researcher prepared all subjects for all sessions.

Subjects warmed up with 6 – 10 repetitions of bar-only squats, 6 – 10 repetitions of bar-only cleans, and dynamic stretching at the discretion of the athlete. For the sprint session (see Table 2), subjects used their regular practice warm-up consisting of various skips, lunges, dynamic stretches, and short sub-max sprints. The subjects rested for a minimum of 5 minutes prior to testing.

Testing Protocol

All testing was completed within a 3-week time window during the track preseason. The subjects were familiar with the exercises to be performed from their regular strength and conditioning training.

Sprint Start (SS): A regular starting block on an indoor track was used. The subjects used their individual block set-up. The primary investigator called "On your mark, Set, Go" upon which the subject started through the 5 m mark.

Squat (S): The elastic band was adjusted such that the knee joint angle was 90° when the subject's hamstrings touched the rubber band in the down movement.

All squats were initiated from an upright position. The athletes were instructed to push upwards as hard and as fast as possible after touching the elastic band. This resulted in a jump with all but the heaviest load. S was performed with 0 (broomstick), 25, 40 and 100% of 1RM.

Power Clean (PC): In this study power clean was defined as a version of the clean without a split and without too much front squat as opposed to a full split clean or a full squat clean used in Olympic weightlifting. In PC with the empty bar, the bar was placed on blocks to obtain the same starting height as when loaded with standard diameter weight plates. PC was performed with 30, 50, 75 and 100% of 1RM.

Power Hang Clean (PHC): The starting position for the PHC placed the bar just above the patella. PHC was performed with 30, 50, 75 and 100% of 1RM.

Each athlete was tested on 3 separate days. Table 2 outlines the testing schedule.

Table 2 Testing schedule.

Session 1		Session 2		Session 3	
Exercise		Exercise		Exercise	
SS (3 trials)	Sprint start over 5 m	1S0 (3 trials)	Single-leg squat jump 0% 1RM load, left and right	S0 (3 trials)	Squat jump with 0% 1RM load
S25 (3 trials)	Squat jump with 25% 1RM load	PHC30 (3 trials)	Power hang clean with 30% PC 1RM	PC30 (3 trials)	Power clean with 30% PC 1RM
S40 (3 trials)	Squat jump with 40% 1RM load	PHC50 (3 trials)	Power hang clean with 50% PC 1RM	PC50 (3 trials)	Power clean with 50% PC 1RM
Smax (1 trial)	Squat with max. load (1RM)	PHC75 (3 trials)	Power hang clean with 75% PC 1RM	PC75 (3 trials)	Power clean with 75% PC 1RM
		PHCmax (1 trial)	Power hang clean with max. load (1RM)	PCmax (1 trial)	Power clean with max. load (1RM)

Exercise order within a session was not randomized. Exercises progressed from lighter to heavier loads and athletes rested 1 – 4 minutes between trials.[96,143] Some athletes were tested on consecutive days while others had one or more days of rest in between testing sessions. During testing little to no verbal encouragement was given as it was felt that the athletes were highly self-motivated. However, on occasion movement cues were given, such as “sit back” or “chest up”.

Data Analysis

Marker trajectories from Vicon were exported to Matlab version 7.9.0 (MathWorks, Inc., Natick, MA, USA) for further data processing.

The following time definitions were used:

T_0, start of movement: For all trials, this was determined visually in Vicon by the principal investigator. The indicator in S, PC, PHC was the frame with the smallest knee angle prior to the start of upward bar displacement. For SS, the frame with the first discernible hip displacement was identified as T_0.

$T_{toe-off}$: For trials with clearly discernible lift-off of the tip toe marker from the ground, $T_{toe-off}$ was determined visually in Vicon as the frame just before the tip toe marker left the ground. In SS it was the frame just before the tip toe marker of the front leg left the front starting block. For all other trials $T_{toe-off}$ was calculated in Matlab as the frame with maximum pelvis height.

T_0 and $T_{toe-off}$ were used to find the fastest trial per exercise which was then analyzed further. 3D angle data for ankles (tibia-foot), knees (femur-tibia), and hips (thorax-femur) were exported to MatLab.

Angles were smoothed (zero-lag Butterworth filter with sampling frequency 250 Hz, 2nd order, cut-off frequency

12 Hz,[123,145] and differentiated to obtain angular velocities. Velocities were then smoothed with the same filter and differentiated to obtain angular acceleration. Acceleration was smoothed again with the same filter.

Acceleration was calculated within T_0 and $T_{toe-off}$ for the same side leg used in the front block of the SS (front leg). Angular acceleration in all exercises is about the x-axis (flexion-extension).

Statistical analysis was conducted with SPSS version 19.0 (SPSS Inc., Chicago, IL, USA). After checks for outliers and normality, one-way ANOVAs for repeated measures between exercises were performed for minimum (amin) and maximum (amax) angular accelerations of hip, knee and ankle. Least significant difference (LSD) was used as a post-hoc procedure. Level of significance was set at $p \leq 0.05$.

A repeated measures, one-way ANOVA was calculated on the T_0 to $T_{toe-off}$ times for all exercises followed by LSD. The mean times of Smax and PCmax were found to be significantly different from all other exercises. As their temporal behavior was not comparable to any of the other exercises, they were excluded from further analysis.

Results

Figure 1 shows exemplary angular acceleration curves of ankle, knee and hip joints in the block start of one subject. Figures 2 - 4 provide the ankle, knee and hip joint acceleration curves in the block start of all subjects.

Figure 1 Angular acceleration of ankle, knee and hip joints during sprint start in subject 2.

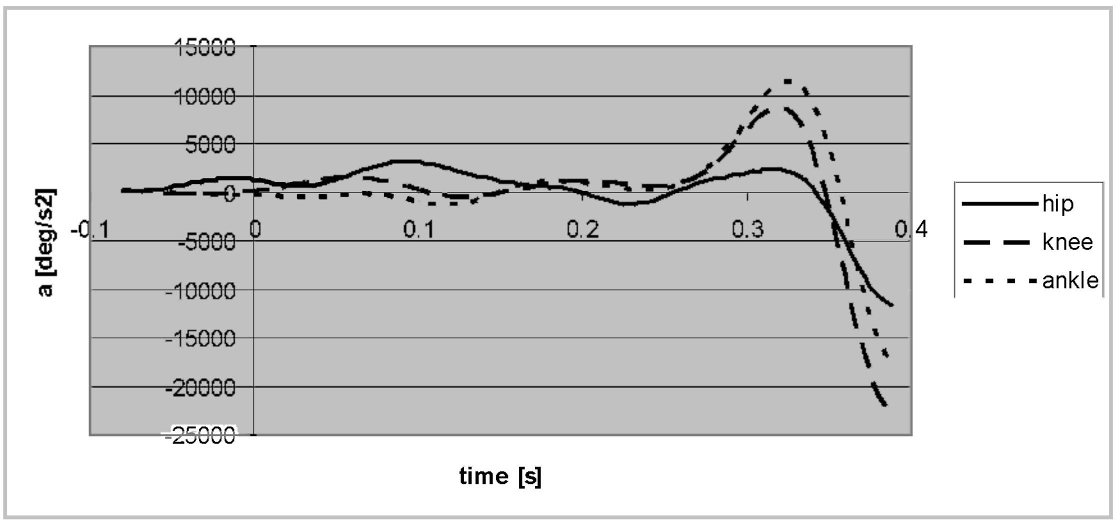


Figure 2 Angular acceleration of ankle joint during sprint start in all subjects.

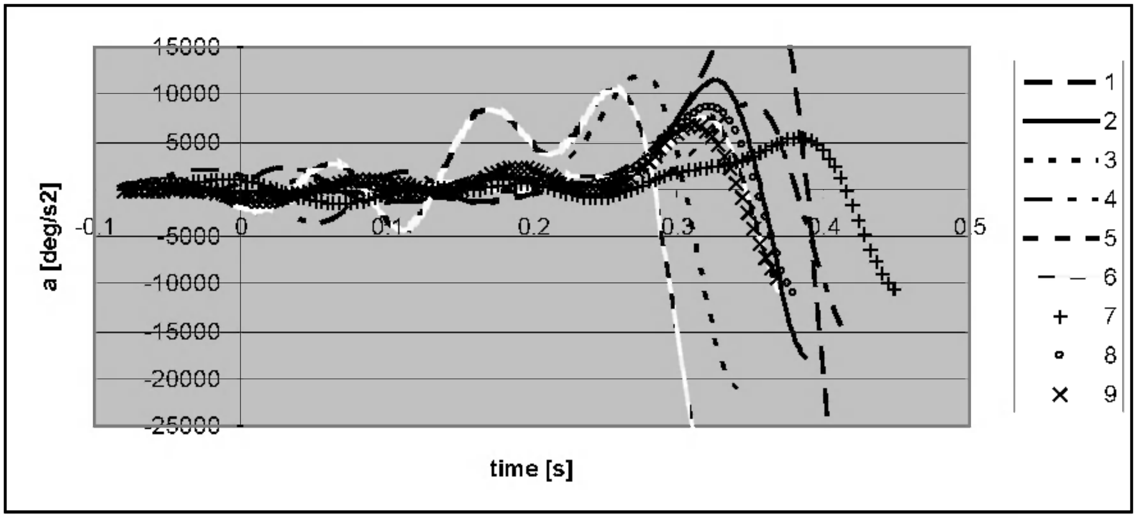


Figure 3 Angular acceleration of knee joint during sprint start in all subjects.

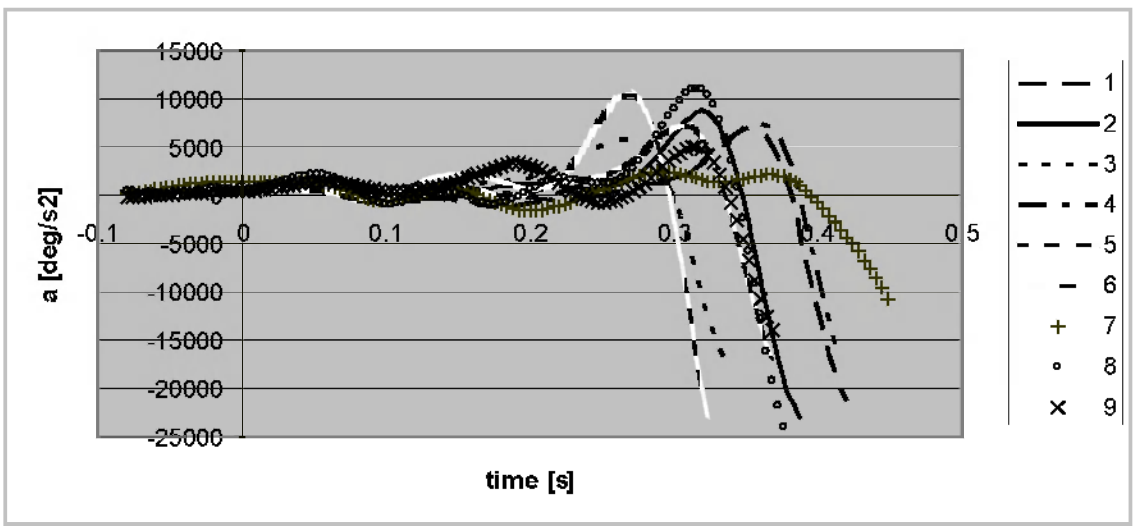
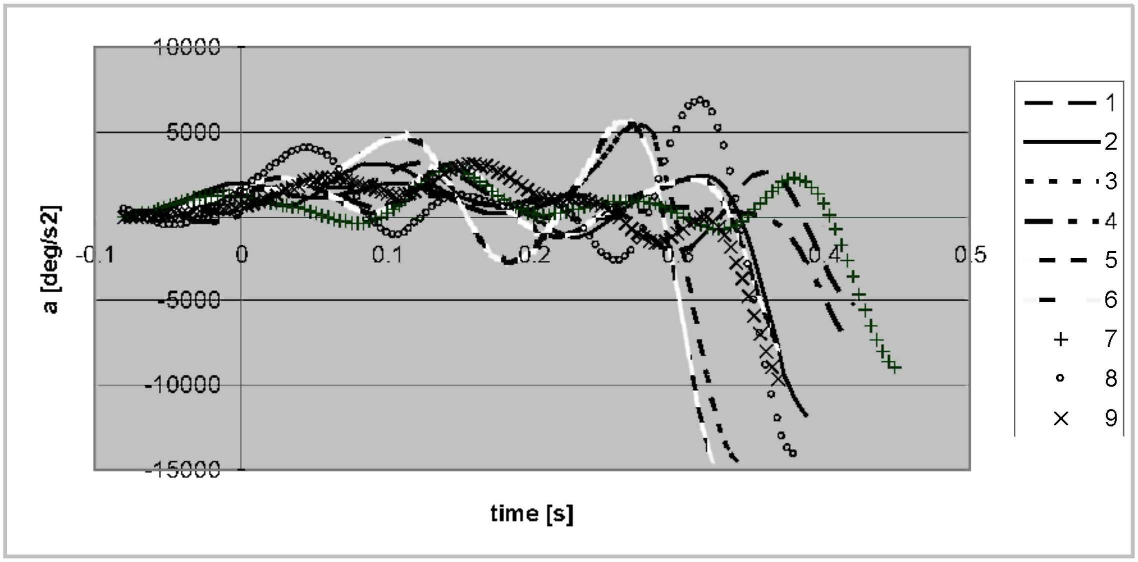
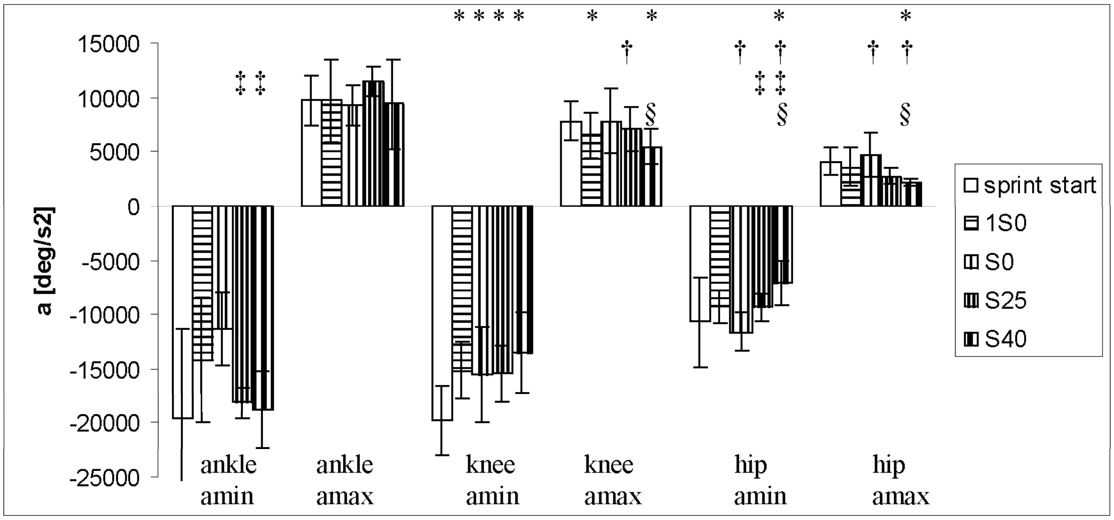


Figure 4 Angular acceleration of hip joint during sprint start in all subjects.



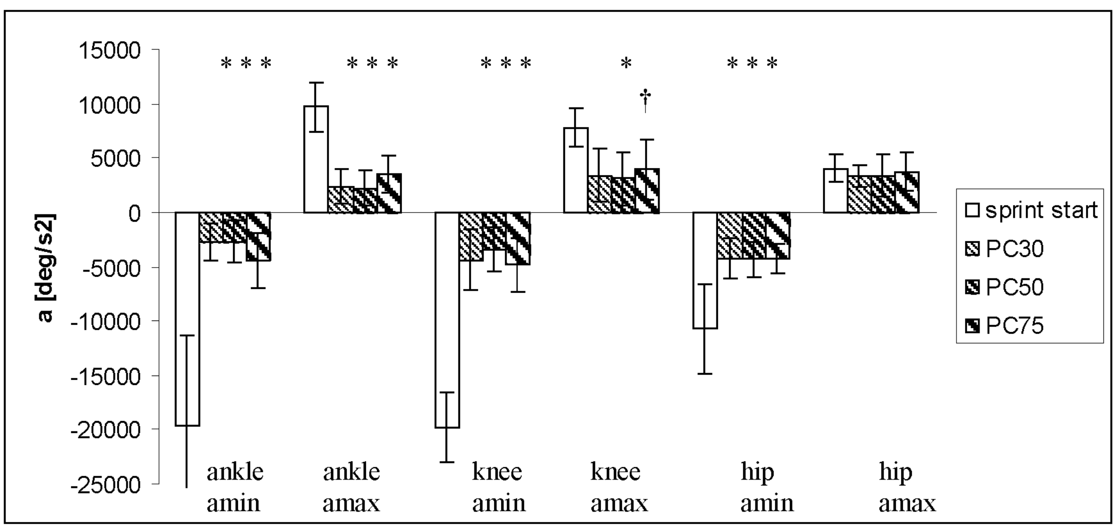
Figures 5 - 10 compare the minimum and maximum angular accelerations in the different exercises to the sprint start. F(13,39) for ankle amin was 11.6, for ankle amax was 11.2, for knee amin was 53.4, for knee amax was 3.4, for hip amin was 23.4, and for hip amax was 2.0.

Figure 5 Angular acceleration of ankle, knee and hip joints in sprint start vs. squat at different loads (mean ± SD).



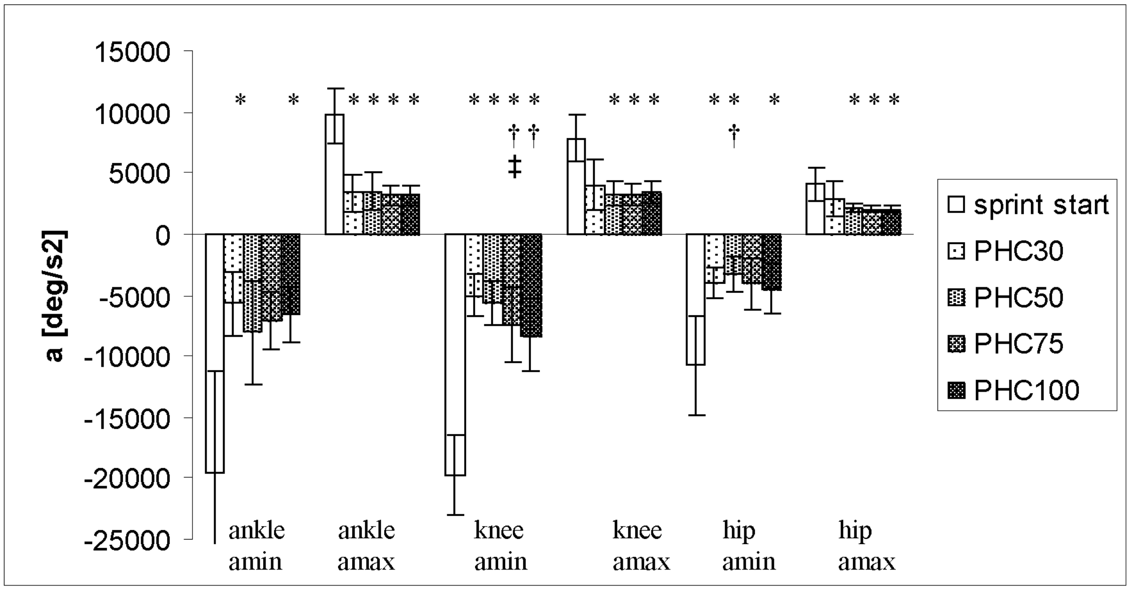
* Significantly different to sprint start (p ≤ 0.05).
† Significantly different to 1S0 (p ≤ 0.05).
‡ Significantly different to S0 (p ≤ 0.05).
§ Significantly different to S25 (p ≤ 0.05).

Figure 6 Angular acceleration of ankle, knee and hip joints in sprint start vs. power clean at different loads (mean ± SD).



* Significantly different to sprint start (p ≤ 0.05).
† Significantly different to PC30 (p ≤ 0.05).

Figure 7 Angular acceleration of ankle, knee and hip joints in sprint start vs. power hang clean at different loads (mean ± SD).



* Significantly different to sprint start ($p \leq 0.05$).
† Significantly different to PHC30 ($p \leq 0.05$).
‡ Significantly different to PHC50 ($p \leq 0.05$).

Figure 8 Angular acceleration of ankle joint in squat vs. power hang clean vs. power clean at different loads (mean ± SD).

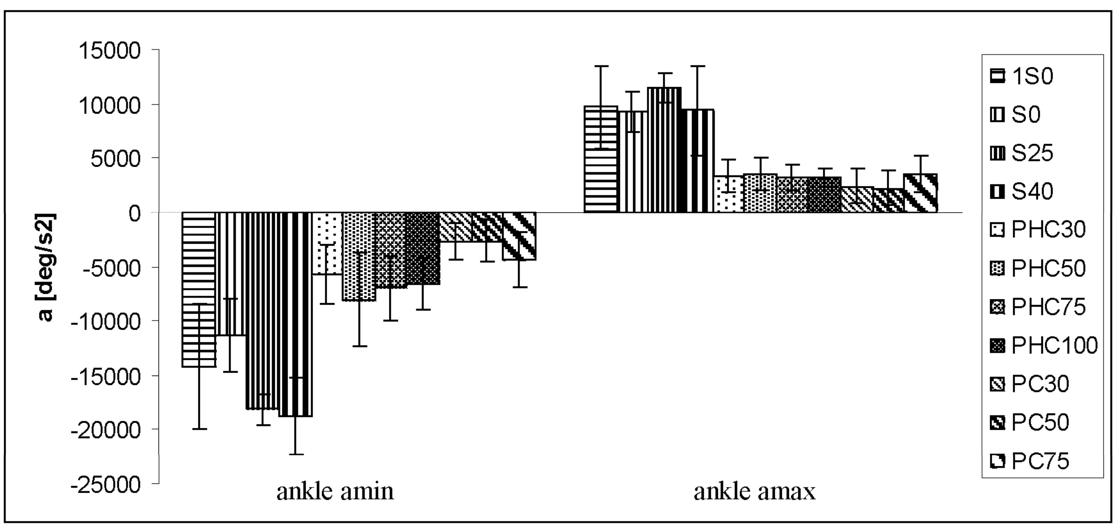


Figure 9 Angular acceleration of knee joint in squat vs. power hang clean vs. power clean at different loads (mean ± SD).

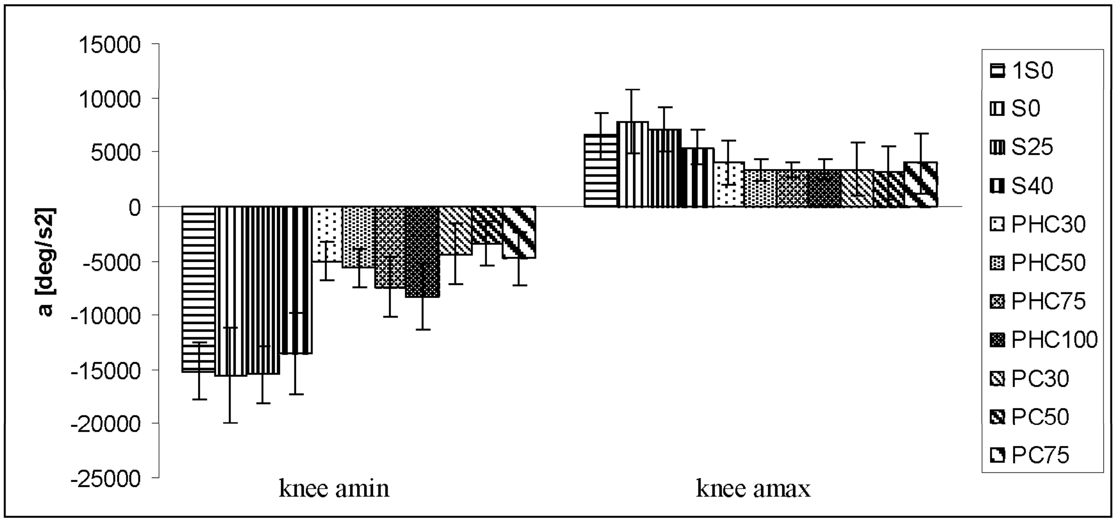
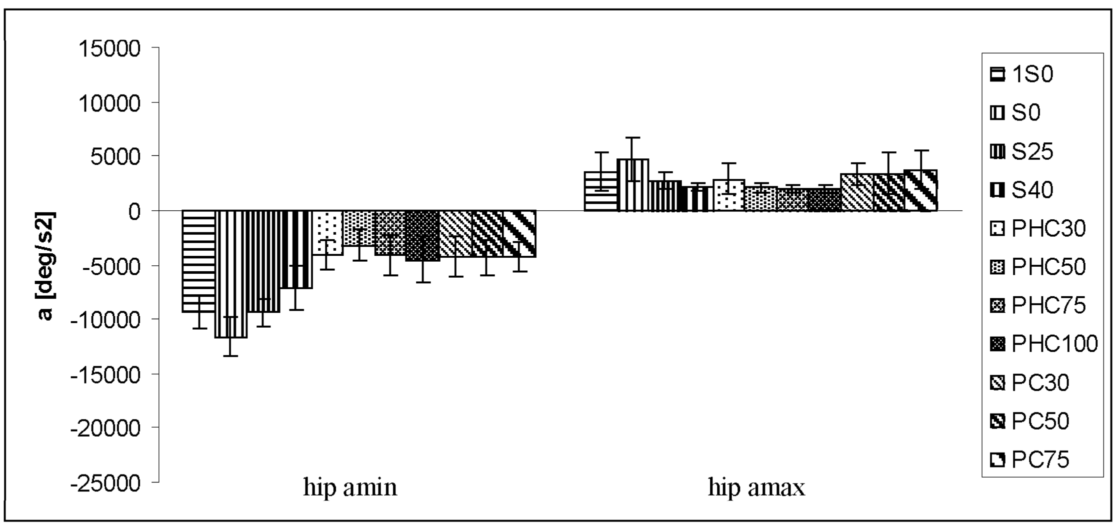


Figure 10 Angular acceleration of hip joint in squat vs. power hang clean vs. power clean at different loads (mean ± SD).



The following findings emerged from the one-way, repeated measures ANOVAs:

a) Angular accelerations differed mainly between groups of exercises (SS and squats vs. PC vs. PHC), less so within the groups.

b) Only for PHC in the minimum angular knee acceleration and for S in the minimum hip acceleration were load changes significantly related to acceleration changes.

c) PHC (knee amin) and S (hip amin) behaved opposite in their respective load-acceleration patterns: Load increase led to acceleration increase in the PHC, whereas load increase resulted in acceleration decrease in the S.

d) Within the PHC, ankle, knee amax and hip accelerations were inconspicuous.

e) Within the PC, virtually none of the angular accelerations seemed to be affected by load changes.

f) Within the squat exercises, only sporadic significant differences were observed other than for hip amin.

g) PC and PHC30 had similar knee amax and hip amax acceleration as SS and S.

h) No exercise decelerates the knee joint (knee amin) as fast as SS.

i) The mean ankle, knee and hip angular acceleration values in the squat exercises, in particular the low-load S0, 1S0 and S25, resembled fairly closely the values measured in the SS.

Discussion

It was hypothesized that increasing loads would lead to significant changes in angular accelerations. This hypothesis was partially confirmed for the minimum angular knee acceleration in power hang cleans and for the minimum hip accelerations in light to moderate load squat jumps.

Interestingly, the load-acceleration relation in these two exercises was reversed in that heavier loads produced higher accelerations in the PHC. Possibly, in order to successfully lift heavier loads, the reversal of direction from extension to flexion at the transition to the drop-under phase had to occur faster, resulting in an increase in minimum angular knee acceleration. The minimum angular hip acceleration showed a similar, statistically non-significant, tendency (Figure 10). In squat jumps, however, there is no drop-under phase, so increasing load should more directly lead to decreasing acceleration (force-velocity curve). Maximum knee and maximum hip angular accelerations behaved similarly, albeit not statistically significant (Figure 9, 10). It could be speculated that the lack of any clear load-acceleration relationship in PC might be due to a combination of the acceleration-reducing squat-like movement in the beginning and the acceleration-increasing hang clean towards the end of a PC.

SS and no- or low-load squat jumps usually reported the highest positive and negative angular accelerations in ankle, knee, and hip. Their mean values were 2 - 4 times higher than the means from PC and PHC. The results of this study seem to indicate that the squat exercises 1S0, S0 and S25 are more specific to lower-limb acceleration patterns of the SS than are S40 and any of the PC or PHC loads. Thus, they should be more effective in achieving performance improvements and more efficient when practice time is limited. However, power cleans may provide a reasonable alternative, specifically for training knee and hip joint acceleration.

Research into the correlation of short distance sprint times with heavy squats[65,97] vs. unloaded jumps[59,104,136] as well as studies about the load that maximizes power output in squats and jumps[6,11,32,33,54,57] corroborate the finding in this study that bodyweight-only and light-load jumps (25% of squat 1RM) mirror explosive-type movements much closer than heavy squats.

This study found mostly significant differences between angular accelerations of the squats and both the power cleans and power hang cleans. This appears to somewhat contradict previous kinematic analyses of snatch vs. vertical jump which was ambiguous on differences in angular displacements and velocities.[2,23]

Surprisingly, none of the PC (except in hip amax) or PHC loads recorded joint accelerations as high as the squat jumps. One reason could be that although the subjects regularly performed high-pulls, cleans and snatches as part of their weight training, they were not well-accomplished in Olympic-style lifting. Additionally, the time interval for analysis was from T_0 to $T_{toe-off}$ (or highest pelvis height). This time span does not include the drop-under phase of the clean which requires fast hip and knee flexion.[5]

No published lower-limb angular acceleration values for the same or similar movements could be found. Therefore, the sprint start block times (not reported here) from this study were compared against the block times of other female sprinters reported in the literature.[27,30,31,55] The angular velocities (not reported here) for the cleans which provide the basis for the calculations of the angular accelerations were also checked against other studies.[5,8,22,76] Both comparisons validated the present results.

The power of the ANOVAs in identifying significant differences was limited by the small number of subjects and by relatively large variations in acceleration values.

Inherent biological movement variability in sprinting has been the subject of several studies.[18,45,95] In fast, multi-joint movements, direct measures of e.g. joint velocity vary significantly greater than an outcome measure such as block velocity.[18,95] Also, the same subject may accomplish the same movement task with different recruitment patterns in consecutive trials.

Compared to the variation in other exercises, the PC typically displayed the largest relative standard deviation, generally greater than 50% of the respective means. Most likely this is due to the observed differences in lifting technique between the athletes. Some initiated the lifts with pronounced knee extension, others with hip extension.

Future studies should: a) examine angular accelerations of the landing (squat) or the catch phase (clean); b) test unilateral exercises, as the sprint start may be considered a predominantly unilateral movement especially in the second half of the block phase; c) test exercises with mostly horizontal rather than vertical movement direction; d) use athletes accomplished in Olympic lifts to verify the results of this study for the power clean and power hang clean.

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