Effects of bicycle fit: the relationship between trunk angle, power, and seat height on metabolic efficiency, kinematics, and muscular timing and function.

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ABSTRACT

Cycling at an optimal saddle height creates favorable performance conditions and prevents injury (Peveler and Green, 2011). A common question for professional cyclists and novices alike is: What seat height and trunk height creates the most favorable riding conditions? In recent studies regarding the kinematics of cycling and anthropometric measurements of bicycle fit, an ideal seat height position based upon knee angle and inseam length has been demonstrated to achieve the best pedaling efficiency (Hamley and Thomas, 1967). This study was conducted to determine the relationship between the effects of seat height, power, and trunk height on muscular activity, energetics, kinematics, and ventilation. A well-trained male cyclist performed 18 treatments at submaximal effort with varying power, seat height, and trunk height, during which kinematic, metabolic, and muscular activity was recorded. All metabolic variables tested were significantly affected by power, seat, and trunk height. Ankle and femur angles were widely affected by power, seat, and trunk height. Knee angles were primarily affected by seat height only. Muscular activity, excluding VLDur was widely affected by power, seat height, and trunk height.

INTRODUCTION

Seat height on bicycles can change the mechanical work the lower limb joints are subjected to. Research conducted beforehand did not provide much information about the effects of trunk height and trunk angle on lower limb kinematics. The most common bike fitting method is to base seat height on knee angle when the knee joint is almost fully extended (Peveler and Green, 2011). There are two main methods for evaluating the most efficient seat height in published and peer reviewed journals. Hamley and Thomas proposed 109% of the inseam as the optimal seat height (Hamley and Thomas, 1967). The inseam is considered the distance from the ischium to the end of the pants or roughly where the tibia ends, while seat height is from the center of the pedal axle to the top of the seat when the crank is parallel to the seat tube. Holmes et al. recommended using a knee angle set between 25[deg] and 35[deg] to prevent injury (Holmes et al., 1994). Shennum and Devries determined that VO_2 progressively increased as saddle height increased: the highest VO_2 occurred at the highest experimental setting of 112%; the most effective saddle positions in the experiment as measured by lowest VO_2 per unit of work were 100% (Shennum and Devries, 1976). Overuse injuries are also common in cycling due to the repetitive nature within a fixed position.

Peveler, Johnson and Palmer observed the importance that dynamic measurements are used in addition to the conventional static bike fitting method because knee angle and ankle angle were discovered to change during constant cycling. They also noted the average increase of 36% in plantar flexion measured while stationary versus pedaling, in addition to an average 17% increase in knee angle under the same conditions (Peveler et al., 2012). There are no published studies to examine how bike fit affects kinematics of lower limbs with a change in power.

The primary purpose of this study was to manipulate power, seat height, and trunk height to determine how they affect muscular activity, energetics (cycling economy), movement, and ventilation. We also analyzed the angles of the femur, knee, and ankle, and the timing of their extremas relative to muscular onset and offset of the gluteus maximus (GL) and biceps femoris (BF), vastus lateralis (VL), and the gastrocnemius (GA), respectively.

We tested the following hypotheses:

Kinematics

As seat height and power increase, we predict maximum (max) knee and ankle angles to increase, and as power and seat height decrease, we expect minimum (min) knee and ankle angles to decrease. We do not expect the knee and ankle (min) and (max) angles to change because the seat height changes the distance the muscles have to lengthen and contract, while trunk height change does not.

Phase Lag

As seat height increases, we predict the VL and BF onset/offset in relation to the min knee and femur angle, as well as max knee and femur angle to decrease. The decrease is due to increasing the joint angle, while keeping the same cadence. GA onset/offset relative to min and max ankle angle will increase as seat height increases. When power increases, we predict VL, BF, GA, onset/offset relative to min and max knee, femur, and ankle angles will decrease as cadence remains constant. As trunk height increases, we predict the VL, BF, and GA onset time relative to the min knee, femur, and ankle angles to remain the same. We expect that as seat height increases, phase lag will not be affected.

Muscular Activity

We expect that a intermediate seat and trunk height will result in the highest metabolic efficiency. We expect as seat height increases, the duration of the vastus lateralis, gastrocnemius, biceps femoris and gluteus maximus will increase. As power increases, we expect the duration of VL, GA, BF, and GL to remain the same because cadence stays the same. Since cadence is staying the same, the muscles will have to work harder to maintain a higher power. As seat height and power increase, we expect the amplitude of VL, GA, BF, and GL to decrease. When trunk height increases, we predict the duration and amplitude of the EMG for VL, GA, BF, and GL to remain the same. We also expect as power increases, phase lag of the onset and offset of the VL, BF, GA and GL relative to their minimum and maximum joint angles will remain the same. We expect that cycling economy, measured in metabolic efficiency, increases as seat height nears a value of 109% of the inseam. We expect that as power and trunk height varies, there would be no difference in min or max joint angles.

Metabolic

As seat height increases, we predict HR, VE, VO2, RER, breathing frequency and volume to increase while efficiency will decrease. Overall, efficiency will decrease as the seat height strays further from the intermediate value because optimal cycling form will be harder to keep consistent. As power increases, we predict HR, VE, VO2, RER, Effic, BrFreq, and BrVol to increase. As trunk height increases, we predict HR and BreFreq to decrease because the diaphragm will be able to expand more, thereby taking in larger breaths of air less frequently which will cause the heart rate to drop. As trunk height increases, VE, VO2, RER, Effic, and BrVol will all increase because the body is better equipped to breath in with more efficiency when stretched upright and not bent or leaning over.

MATERIALS AND METHODS

The test subject in this research experiment was Sam (M, 184 lbs, 74 in). We used a cross-sectional experimental design totaling 18 trials. The three treatment variables were: 2 powers, 3 saddle heights, and 3 trunk heights. Cadence was to remain consistent as a control. All trials were conducted on a Cannondale 56cm bicycle (Cannondale Inc. Wilton, Connecticut, US) in a TACX training stand (Garmin Llc., Netherlands).

Power, cadence, and heart rate is recorded using a Powertap Cycling Computer (Saris, Madison, WI, USA). The targeted power treatments were 155W and 280W. Experimental mechanical power is recorded for control purposes. Sam's experimental power varied within 10 W of the target power. Experimental cadence was also recorded for control purposes. Sam's experimental cadence averaged 90 rpm with a variance of approximately 5 rpm at the high power treatment, but approximately 10 rpm at the low power treatment.

Seat height is measured from the center of the pedal axle on the bicycle crank arm to the top of the bicycle seat. The intermediate (S2) seat height was determined by multiplying inseam length by 1.10. Low (S1) and high (S3) seat heights were 98% and 102% of the intermediate seat height, respectively. Trunk height is measured using the distance from the shoulder to the ground while Sam was seated on the bike in different riding positions. Trunk heights were recorded while Sam was on the bicycle with the seat in the intermediate height; low trunk height (T1) was recorded when Sam had his hands placed in the "drops" of the bicycle handlebars, intermediate trunk height (T2) was recorded while Sam was had his hands placed on the brake hoods of the bicycle handlebars, and high trunk height (T3) was recorded when Sam had his hands on the "flats" of the bicycle handlebars. Once these initial trunk heights were recorded, their respective heights increased or decreased by 2 cm to account for the +/- 2 cm decrease or increase in seat height. To obtain consistent trunk heights across treatments, a horizontal wooden pole was laid across Sam's shoulders (Fig. 1A).

The following was used to record muscular activity and kinematic data: Sam was equipped with six stick-on adhesive reflectors on the skin of his shoulder, hip, top of femur, knee, ankle, and metatarsal (Fig. 1A). A Panasonic Lumix digital camera (Panasonic, Kadoma, Osaka) set to record 1000 frames per second recorded Sam's movement during each trial, further used to obtain kinematic data. Reflective parts of the bike and subject were taped off using black tape as the MAXTRAQ (Innovision Systems Inc, Michigan U.S) program used to find joint angles will pick up interference from other reflective surfaces in the frame. In order to synchronize the timing of the video data to the EMG data, an LED synchronizing light flashed one-second after the start of the LabChart EMG recording.

To record muscular activity, 2 EMG cables with disposable patch electrodes connected to the Powerlab 16SP analog to digital converter with LabChart software (ADInstruments, New Zealand). Two electrodes were placed on the skin superficial to Sam's vastus lateralis, biceps femoris, gastrocnemius, and gluteus maximus. The 18 trials were not performed in random order as fatigue is not a concern during a short trial period. Each trial recorded 30 seconds to a minute of data. All EMG data was collected used a 1K sec^{-1} sampling rate along with a high pass filter with a cut off frequency of 30 Hz. Kinematic data was acquired by digitizing the treatment video files using MAXTRAQ . The angle conventions were: a two point angle for the femur defined by the ray of the femur relative to the ray of the horizontal axis and a three point angle for trunk defined by the ray of the femur and the ray of the lower back to the pelvis, knee angle defined by the points of the ankle, knee and hip, and ankle angle defined by a point on the tarsals, ankle/talus and the knee (Figs. 1BCD). Once all the angles were digitized, the maximum and minimum angles of the knee, femur, and ankle, and their respective times were recorded.

The following was used to record metabolic data: We used a spirometer consisting of a mask connected to long tubing that reaches a flow head connected to a mixing chamber. The mixing chamber then leads to the pump then the drying tube and into the gas analyzer which is connected to a spirometer pod. A spirometer was used to measure $\%O_2$ and CO_2 intake/output along with total Flow in liters. Once the spirometer is calibrated, we began to collect data with Labchart using a 1K sec^{-1} sampling rate and a low pass filter with a cutoff frequency of 15 Hz. All 18 trials are performed in a random order due to potential fatigue and experimental variations. Six minutes of data was recorded, with the assumption that metabolic steady state conditions would be met within three minutes.

For data analysis we did a three way analysis of variance (ANOVA) with fixed and crossed variables of saddle height, trunk height, power. Our threshold for statistical significance was $P \leq 0.01$.

The abbreviations throughout this report are as follows: CycDur, cycle duration; AKmin, minimum knee angle; AKmax, maximum knee angle; KAngExc, knee angular excursion; AAmin, minimum ankle angle; AAmax, maximum ankle angle; AAngleExc, ankle angular excursion; AFmin, minimum femur angle; AFmax, femur angle maximum; FAngExc, femur angular excursion; HR, heart rate; MechPower, mechanical power; VE, minute volume; VO2, volume of O_2 consumed; RER, respiratory exchange ratio; Effic, efficiency; BrFreq, breathing frequency; BrVol, breath volume; Cad, cadence; VL, vastus lateralis; GA, gastrocnemius; BF, biceps femoris; GL(maj), gluteus maximus major burst; GL(full), gluteus maximus full burst; Dur, duration; Amp, amplitude; VL, vastus lateralis; GA, gastrocnemius; BF, biceps femoris; GL(maj), gluteus maximus major burst; GL(full), gluteus maximus full burst; Dur, duration; TKmin, time of knee minimum angle; TKmax, time of maximum knee angle; TAmin, time of minimum ankle; TAmax, time of maximum angle; TFmin, time of minimum femur angle; TFmax, time of maximum femur angle.

RESULTS

Kinematic

19 out of 30 main effect kinematic F-tests were significant. As power increased, all ankle angles and AFmin significantly decreased and AAngExc and FAngExc, significantly increased (Table 1; Fig. 2A). As seat height increased, all knee and ankle angles and FAngExc increased significantly, while femur angles decreased significantly (Table 1; Fig. 2B). As trunk height increased, all ankle and femur angles increased significantly and AKmin significantly decreased (Table 1; Fig. 2C).

Six two-factor F-tests were significant. The effects of power depended on the effect of seat height and trunk height. The main effects of seat height and trunk height were significant on AFmax, but the main effect of power was not significant. As seat height and power increased, AFmax decreased significantly (Table 1; Fig. 2D). As trunk height and power increased, AFmax increased significantly (Table 1; Fig. 2E).

Metabolic

20 out of 21 main effect metabolic F-tests were significant. As power increased, all metabolic dependent variables significantly increased (Table 2; Fig. 3A). As seat height increased, HR increased significantly and RER decreased significantly (Table 2; Fig. 3B). As trunk height increased, VE, Effic, and BrFreq decreased significantly, and VO2 and BrVol increased significantly (Table 2; Fig. 3C).

BrFreq and VE were lowest at the intermediate seat height and highest at the high seat height (Table 2). Effic was highest at the low seat height and lowest at the intermediate seat height (Table 2). RER was highest at the intermediate seat height and lowest at the low seat height (Table 2). HR was highest at the intermediate trunk height and lowest at the high trunk height (Table 2).

The effects of seat height on BrVol depended on the effects of power and trunk height. The main effects of power and trunk height were significant, but the main effect of seat height was not significant. At the low power treatment, BrVol increased with seat height and at the high power treatment, BrVol was highest at the intermediate seat height and lowest at the high seat height (Table 2; Fig. 3D). At the low seat height, BrVol decreased significantly as trunk height increased (Table 2). At the intermediate and high seat height, BrVol was highest at the high trunk height, while BrVol was lowest intermediate seat height and low trunk height and at the high seat height and intermediate trunk height (Table 2; Fig. 3E).

Muscular Activity

23 of 24 main-effect muscular activity F-tests were significant. The was no significant effect of power, seat height, and trunk height on VLDur or GL(full)Dur (Table 3). VLAmp, BFDur, BFAmp,and GAAmp increased significantly as power increased (Table 3; Fig. 4A; Fig. 5AB). As seat height increased, GADur and GAAmp increased significantly and GL(maj)Amp decreased significantly (Table 3; Fig. 4B). BFAmp decreased significantly as trunk height increased (Table 3). GAAmp increased significantly as trunk height increased (Table 3; Fig. 4C). BFAmp, GL(maj)Dur, GL(maj)Amp is highest at intermediate seat height and lowest at low seat height (Table 3).

All two-factor F-tests were significant. The main effect of power had a significant effect on VLAmp and BFDur, but seat height did not have a significant effect. At low power, VLAmp and BFDur are highest at the intermediate seat height and lowest at the low seat height (Table 3; Fig. 4D). At high power, VLAmp and BFDur are highest at the low seat height and lowest at the intermediate seat height (Table 3). At the low and intermediate seat height, BFDur is highest at the intermediate trunk height and lowest at the highest trunk height (Table 3; Fig. 4E). At the high seat height, BFDur increases as trunk height increases (Table 3; Fig, 4E). The main effect of seat height had a significant effect on GL(maj)Dur, but trunk height did not. At the high and seat height, GL(maj)Dur decreases as trunk height increases (Table 3). At the intermediate seat and trunk height, GL(maj)Dur is lowest and highest at the high trunk height (Table 3). The main effect of seat and trunk height had significant effects on GL(maj)Dur, but power did not. At low power, GL(maj)Dur was highest at intermediate seat and trunk height and lowest at high seat and trunk height and the opposite of these effects at high power (Table 3).

Phase Lag

23 of 24 main effects pertaining to phase lag were significant. As power increased, VLOffTKmax, GAOnTAmin, GAOffTAmax, BFOnTFmin, BFOffTFmax, GL(maj)onTFmin, and GL(maj)offTFmax decreased significantly (Table 4; Fig. 6A). The values VLOnTKmin, VLOffTKmax, GAOnTAmin, GAOffTAmax, BFOnTFmin, GL(maj)onTFmin, and GL(maj)offTFmax were lowest at the low seat height and highest at the intermediate seat height (Table 4; Fig. 6B). BFOffTFmax increased significantly as seat height increased. VLOnTKmin, BFOffTFmax, and GL(maj)offTFmax were highest at the low trunk height and lowest at the intermediate trunk height (Table 4). VLOffTKmax, GAOnTAmin, and GAOffTAmax were lowest at the intermediate trunk height and approximately equal at the low and high trunk heights (Table 4; Fig. 6C). BFOnTFmin and GL(maj)OnTFmin were lowest at the intermediate trunk height and highest at the high trunk height (Table 4).

Power did not significantly affect VLOnTKmin, but the main effects of seat height and trunk height was significant (Table 4; Fig. 6D). At the low and high power treatment, VLOnTKmin was lowest at the low seat height and highest at the intermediate seat height (Table 4). At the low power treatment, VLOnTKmin decreased as trunk height increased (Table 4; Fig. 6E). At the high power treatment, VLOnTKmin was lowest at the intermediate trunk height and highest at the high trunk height (Table 4; Fig. 6E).

DISCUSSION

When cycling, it is important to adjust seat height and trunk position to maximize efficiency and prevent injury. Previous studies have suggested using 109% of the inseam for optimal saddle height (Hamley and Thomas, 1967). Alterations in body position and specifically seat height can affect muscle activation and pedaling (Hug and Dorel, 2009). The purpose of this study was to examine the effects of saddle height, trunk height, and power on cycling economy, kinematics, and muscular activity.

Kinematics

Our main effect kinematic F-tests revealed about ⅔ significant results. Contrary to our prediction, the ankle angles and femur angle decreased as power increased (Fig. 2A). However, the AAngExc and FAngExc both increased as power increased (Fig. 2A). Saddle height affects kinematics of the ankle and/or knee (Price, 1997). We were correct in predicting as the seat height increased, (max) knee and ankle angle increased significantly, due to a larger range of motion presented by the seat height increase which allows for a greater angle in between joints of the knee and ankle. We originally did not believe that trunk height would have a significant effect on the knee, femur, and ankle angles because they are relatively independent of trunk position. As trunk height increased, the ankle and femur angles also increased, while AKmin decreased. Decrease in AKmin could be due to as trunk height increased, the body changes towards a more upright position releasing tension from the lower back and glutes allowing for a smaller rotation of the knee hand position changing as trunk height increased, a more relaxed grip could allow for a more comfortable stance and lower the (min) knee angle.

Metabolic

We were correct in our assumption that as power increases, all metabolic processes will increase as well. When trunk height increased, breathing volume and VO2 increased significantly because in a more upright position, the body is able to draw in more oxygen per breath. This would also result in breathing frequency to decrease along with efficiency. What was interesting is efficiency was highest at the lowest seat height because we thought efficiency would be the greatest at the intermediate levels of seat height and trunk angle since the rider is experienced in riding in that stance. Overall, trunk and power both had significant effects on the metabolic processes of cycling, while seat height had no significant effect. Seat height has no effect on the muscle activity because the seat height changes angles of the joints. The power increasing requires more energetic input to reach the target power which in return will have an effect on metabolic interactions.

Muscular Activity

We predicted that the duration of muscular contraction would increase as the seat height increases, because the knee and femur angles increased, so they must travel an increased distance. This was the case for some, but not all EMG durations. GADur and GAAmp increased significantly as seat height increased.

Because the seat height increased, the GA was forced to compensate by stretching more to reach the bottom of the pedal stroke. Amplitude of BF decreased as trunk height increased, which disproved our hypothesis that trunk height would have no significant effect on duration or amplitude. Trunk angle manipulated by grip can change variously throughout the trunk from shoulders to the hip (Faria, 1978). The grip changes can affect muscle activity by affecting the angle of the hip and femur. VLAmp, BFDur, BFAmp, and GAAmp all significantly increasing with power proving our previous hypothesis.

Phase Lag

We predicted the onset/offset times of muscle activity and (max) and (min) knee angle to decrease as power decreased because the cadence was kept the same. Our results showed a significant decrease in almost all muscle onset/offset activity relative to joint angles. What was interesting is the values of the phase lag were lowest at the lowest seat height and higher at the intermediate seat height. We predicted the phase lags would decrease as seat height increased and determined this to be wrong. The lower the seat, the smaller the joint angle and less time between muscle activation and (max) or (min) joint angle.

One major limitation in our research was only testing one subject. Most studies on cycling movement involve multiple subjects from both genders participating in the research. Due to time constraints we were not able to record more than 6 minutes of metabolic data per trial. However, our rider was experienced and was able to reach a metabolic steady state with ease. In future experimental design we would test different seat types to see the effect on EMG activation especially in the gluteus maximus. We could also test the effects of wind resistance on different trunk heights. Trunk height is not only important to joint angles and efficiency, but important to a rider when experiencing resistance from the environment. Along with trunk angle, we could run tests where the rider cycled on incline and decline planes to see the effect on efficiency as well as muscle activation.

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Table 1. Summary of *F* and *(P)* values from analysis of variance (ANOVA) performed separately on each kinematic dependent variable.

	ANOVA effect					
Dependent variable	Power (P) (d.f. = 1,72)	Seat (S) (d.f. = 2,72)	Trunk (T) (d.f. = 2,72)	S x P (d.f. = 2,72)	T x P (d.f. = 2,72)	T x S (d.f. = 4,72)
CycDur	0.27 (0.598)	0.27 (0.757)	0.27 (0.757)	0 (0.994)	1.4 (0.251)	2.81 (0.031)
AKmin	0.92 (0.34)	182.38 (<0.001)	6.52 (0.002)	1.68 (0.193)	0.67 (0.511)	2.7 (0.037)
AKmax	5.35 (0.023)	104.74 (<0.001)	1.4 (0.251)	0.41 (0.664)	1.24 (0.294)	0.83 (0.507)
KAngExc	3.61 (0.061)	31.28 (<0.001)	0.2 (0.817)	0.27 (0.762)	1.1 (0.337)	1.32 (0.269)
AAmin	303.14 (<0.001)	12.35 (<0.001)	5.86 (0.004)	0.08 (0.922)	8.73 (<0.001)	8.1 (<0.001)
AAmax	55.77 (<0.001)	579.49 (<0.001)	11.65 (<0.001)	0.96 (0.387)	1.19 (0.308)	3.18 (0.018)
AAngExc	6.91 (0.01)	522.78 (<0.001)	4.42 (0.015)	1.02 (0.363)	0.42 (0.654)	0.45 (0.771)
AFmin	29.49 (<0.001)	207.37 (<0.001)	30.32 (<0.001)	0.42 (0.652)	1.78 (0.174)	3.78 (0.007)
AFmax	2.69 (0.105)	1278.82 (<0.001)	510.79 (<0.001)	4.82 (0.01)	8.13 (<0.001)	17.75 (<0.001)
FAngExc	34.12 (<0.001)	23.57 (<0.001)	0.69 (0.501)	1.04 (0.358)	1.54 (0.221)	3.15 (0.019)

*CycDur, cycle duration; AKmin, minimum knee angle; AKmax, maximum knee angle; KAngExc, knee angular excursion; AAmin, minimum ankle angle; AAmax, maximum ankle angle; AAngleExc, ankle angular excursion; AFmin, minimum femur angle; AFmax, femur angle maximum; FAngExc, femur angular excursion.

Table 2. Summary of *F* and *(P)* values from analysis of variance (ANOVA) performed separately on each metabolic dependent variable.

	ANOVA effect					
Dependent variable	Power (P) (d.f. = 1,36)	Seat (S) (d.f. = 2,36)	Trunk (T) (d.f. = 2,36)	S x P (d.f. = 2,36)	T x P (d.f. = 2,36)	T x S (d.f. = 4,36)
HR	7483.5 (<0.001)	40.1 (<0.001)	35 (<0.001)	9.2 (<0.001)	122.7 (<0.001)	23.2 (<0.001)
MechPower	25021.5 (<0.001)	21.6 (<0.001)	23.3 (<0.001)	36.6 (<0.001)	26.1 (<0.001)	6.5 (<0.001)
VE	4464.4 (<0.001)	29.6 (<0.001)	53.2 (<0.001)	5.8 (0.006)	13.2 (<0.001)	7.5 (<0.001)
VO2	4740.2 (<0.001)	190.9 (<0.001)	115.9 (<0.001)	7.2 (0.002)	139.8 (<0.001)	23.5 (<0.001)
RER	616.6 (<0.001)	17.9 (<0.001)	11.4 (<0.001)	15.2 (<0.001)	14.4 (<0.001)	116 (<0.001)
Effic	28 (<0.001)	181.7 (<0.001)	57.8 (<0.001)	33.9 (<0.001)	49.9 (<0.001)	13.1 (<0.001)
BrFreq	1040.1 (<0.001)	15.8 (<0.001)	84.5 (<0.001)	19.3 (<0.001)	21.2 (<0.001)	24.6 (<0.001)
BrVol	1428.5 (<0.001)	3.3 (0.04)	10.8 (<0.001)	11.8 (<0.001)	7.7 (0.001)	25.5 (<0.001)
Cad	0.5 (0.45)	41.2 (<0.001)	0.9 (0.41)	15.2 (<0.001)	3.7 (0.03)	3.5 (0.01)

*HR, heart rate; MechPower, mechanical power; VE, minute volume; VO2, volume of O_2 consumed; RER, respiratory exchange ratio; Effic, efficiency; BrFreq, breathing frequency; BrVol, breath volume; Cad, cadence.

Table 3. Summary of *F* and *(P)* values from analysis of variance (ANOVA) performed separately on each muscular activity dependent variable.

	ANOVA effect					
Dependent variable	Power (P) (d.f. = 1,72)	Seat (S) (d.f. = 2,72)	Trunk (T) (d.f. = 2,72)	S x P (d.f. = 2,72)	T x P (d.f. = 2,72)	T x S (d.f. = 4,72)
VLDur	0.2 (0.59)	2.9 (0.059)	0.7 (0.466)	1.9 (0.153)	0.9 (0.397)	0.6 (0.628)
VLAmp	178.5 (<0.001)	1.9 (0.144)	0.5 (0.584)	4.8 (0.01)	0.1 (0.877)	3 (0.02)
GADur	1.2 (0.276)	10.2 (<0.001)	0.6 (0.523)	1.4 (0.24)	1.1 (0.332)	3.4 (0.013)
GAAmp	21.4 (<0.001)	11.6 (<0.001)	1.5 (0.217)	0.4 (0.628)	2.1 (0.119)	2 (0.094)
BFDur	56.2 (<0.001)	1.3 (0.263)	5.5 (0.005)	6.1 (0.003)	2.7 (0.072)	3.7 (0.007)
BFAmp	60.3 (<0.001)	8.2 (<0.001)	6.2 (0.003)	1.3 (0.262)	0.2 (0.765)	1.5 (0.196)
GL(maj)Dur	0.1 (0.739)	13 (<0.001)	2.3 (0.105)	1.8 (0.166)	1.7 (0.18)	3.8 (0.007)
GL(full)Dur	0 (0.903)	0.5 (0.594)	0.1 (0.86)	0.5 (0.601)	2 (0.133)	1.3 (0.264)
GL(maj)Amp	0.1 (0.673)	5.3 (0.006)	9 (<0.001)	16.8 (<0.001)	7.6 (0.001)	10.8 (<0.001)
GL(full)Amp	167.8 (<0.001)	242 (<0.001)	108.5 (<0.001)	445.6 (<0.001)	101.4 (<0.001)	24.3 (<0.001)

*VL, vastus lateralis; GA, gastrocnemius; BF, biceps femoris; GL(maj), gluteus maximus major burst; GL(full), gluteus maximus full burst; Dur, duration; Amp, amplitude.

Table 4. Summary of *F* and *(P)* values from analysis of variance (ANOVA) performed separately on each phase lag dependent variable.

	ANOVA effect					
Dependent variable	Power (P) (d.f. = 1,72)	Seat (S) (d.f. = 2,72)	Trunk (T) (d.f. = 2,72)	S x P (d.f. = 2,72)	T x P (d.f. = 2,72)	T x S (d.f. = 4,72)
VLOnTKmin	0.2 (0.598)	450 (<0.001)	443 (<0.001)	408.2 (<0.001)	1291.8 (<0.001)	223 (<0.001)
VLOff TKmax	1295.3 (<0.001)	2736.9 (<0.001)	599.3 (<0.001)	438.5 (<0.001)	1712 (<0.001)	765.6 (<0.001)
GAOnTAmin	171.9 (<0.001)	188.4 (<0.001)	553.8 (<0.001)	152.1 (<0.001)	576.3 (<0.001)	545.5 (<0.001)
GAOffTAmax	1908.8 (<0.001)	3702.6 (<0.001)	808.6 (<0.001)	541.4 (<0.001)	2181.1 (<0.001)	994.9 (<0.001)
BFOnTFmin	219.3 (<0.001)	582.5 (<0.001)	778.2 (<0.001)	561 (<0.001)	1048.2 (<0.001)	897.7 (<0.001)
BFOffTFmax	619.1 (<0.001)	189.4 (<0.001)	1268.4 (<0.001)	211.5 (<0.001)	1366.7 (<0.001)	777.3 (<0.001)
GL(maj)onTFmin	78.7 (<0.001)	433.5 (<0.001)	255.9 (<0.001)	230.4 (<0.001)	594.6 (<0.001)	325.4 (<0.001)
GL(maj)offTFmax	541.5 (<0.001)	441.3 (<0.001)	1018.2 (<0.001)	197.9 (<0.001)	965.9 (<0.001)	451.1 (<0.001)

*VL, vastus lateralis; GA, gastrocnemius; BF, biceps femoris; GL(maj), gluteus maximus major burst; GL(full), gluteus maximus full burst; Dur, duration; TKmin, time of knee minimum angle; TKmax, time of maximum knee angle; TAmin, time of minimum ankle; TAmax, time of maximum angle; TFmin, time of minimum femur angle; TFmax, time of maximum femur angle; Amp, amplitude.

Figure Legends

Fig. 1. Graphics illustrating experimental methods. (A) Reflector placement on the shoulder, hip, top of femur, knee, ankle, and metatarsal used for digitizing kinematics. Trunk height was measured from a dowel-rod was placed across the subject's shoulders to the floor. (B) Knee angle measured as a three-point angle, with the knee as the vertex. (C) Ankle angle measured as a three-point angle, with the ankle as the vertex. (D) Femur Angle measured as a two-point (?) angle relative to the horizontal.

Fig. 2. Main and two-factor effects of independent variables on kinematic dependent variables. (A) As power increased, AAmin decreased significantly (Table 1). The same effect was observed on all ankle angles and AFmin (Table 1). (B) AAMin increased significantly as seat height increased (Table 1). All knee, angle angles, and FAngExc experienced the same effect (Table 1). (C) AFMax increased significantly as trunk height increased (Table 1). All ankle and femur angles experienced the same effect (Table 1). (D) At both high and low power, AFmax decreased significantly as seat height increased (Table 1). (E) At both high and low power, AFmax increased as trunk height increased (Table 1).

Fig. 3. Main and two-factor effects of independent variables on metabolic dependent variables. (A) Effic increased significantly as power increased (Table 2). All metabolic variables experienced the same effect (Table 2). (B) HR increased significantly as seat height increased (Table 2). (C) Effic decreased significantly as trunk height increased (Table 2). VE and BrFreq experienced the same effect. (D) The effects of seat height on BrVol depended on the effects of power and trunk height. At low power, BrVol increased with seat height, while at the high power, BRVol was highest at the intermediate seat height and lowest at the high seat height

(Table 2). (E) At the low seat height, BrVol decreased significantly as trunk height increased, at the intermediate and high seat height, BrVol was highest at the high trunk height, and lowest at the intermediate seat height and low trunk height, as well as at the high seat height and intermediate trunk height (Table 2).

Fig. 4. Main and two-factor effects of independent variables on muscular activity dependent variables. (A) As power increased, GAAmp increased significantly (Table 3). VLAmp, BFDur, BFAmp experienced the same effect (Table 3). (B) GAAmp increased significantly as seat height increased (Table 3). GADur experienced the same effect (Table 3). (C) GAAmp increased significantly as trunk height increased (Table 3). (D) VLAmp and BFDur were significantly affected by seat height only when combined with power. At low power, BFDur was highest at the intermediate seat height and lowest at the low seat height. The pattern is reversed for high power (Table 3). (E) At the low and intermediate seat height, BFDur is highest at the intermediate trunk height and lowest at the highest trunk height (Table 3). At the high seat height, BFDur increases as trunk height increases (Table 3).

Fig. 5. EMGs of VL, GA, BF, and GL during two treatments at varying power conditions. (A) EMGs of VL, GA, BF, and GL during treatment one(low power, intermediate trunk height and seat height). (B) EMGs of VL, GA, BF, and GL during treatment two (high power, intermediate trunk height and seat height). VLAmp, BFDur, BFAmp, and GAAmp increased significantly as power increased (Table 3).

Fig. 6. Main and two-factor effects of independent variables on phase lag dependent variables. (A) GAOffTAmax decreased significantly as power increased (Table 4). This effect was the same for VLOffTKmax, GAOnTAmin, BFOnTFmin, BFOffTFmax,GL(maj)onTFmin,

and GL(maj)OffTFmax (Table 4). (B) GAOffTAmax was lowest at the lowest seat height and highest at the intermediate seat height. The same effect was observed for VLOnTKmin, VLOffTKmax, GAONTAmin, GAOffTAmax, BFOnTFmin, GL(maj)onTFmin, and GL(maj)offTFmax (Table 4). (C) GAOffTAmax was lowest at the intermediate seat height and approximately equal at the low and high seat height (Table 4). The same effect was observed on VLOFFTKmax and GAOnTAmin (Table 4). (D)VLOnTKmin was not significantly affected by power, but was by trunk height and seat height. At low power, the intermediate seat height had the highest VLOnTKmin and was lowest at the low seat height (Table 4). (E) At the low power treatment, VLOnTKmin decreased as trunk height increased (Table 4; Fig. 5E). At the high power treatment, VLOnTKmin was lowest at the intermediate trunk height and highest at the high trunk height (Table 4; Fig. 5E).

Fig. 7. Phase lag of GA offset relative to maximum ankle angle under varying power conditions. The first vertical line indicates offset of GA and the second vertical line indicates maximum ankle angle. (A) EMGs of VL, GA, BF, and GL during treatment one(low power, intermediate trunk height and seat height) compared to kinematic angle data of the ankle, femur, and knee. (B) EMGs of VL, GA, BF, and GL during treatment two (high power, intermediate trunk height and seat height) compared to kinematic angle data of the ankle, femur, and knee. Phase lag of GA offset relative to maximum ankle angle is significantly reduced in treatment two due to the high power conditions (Table 4).

Fig. 1

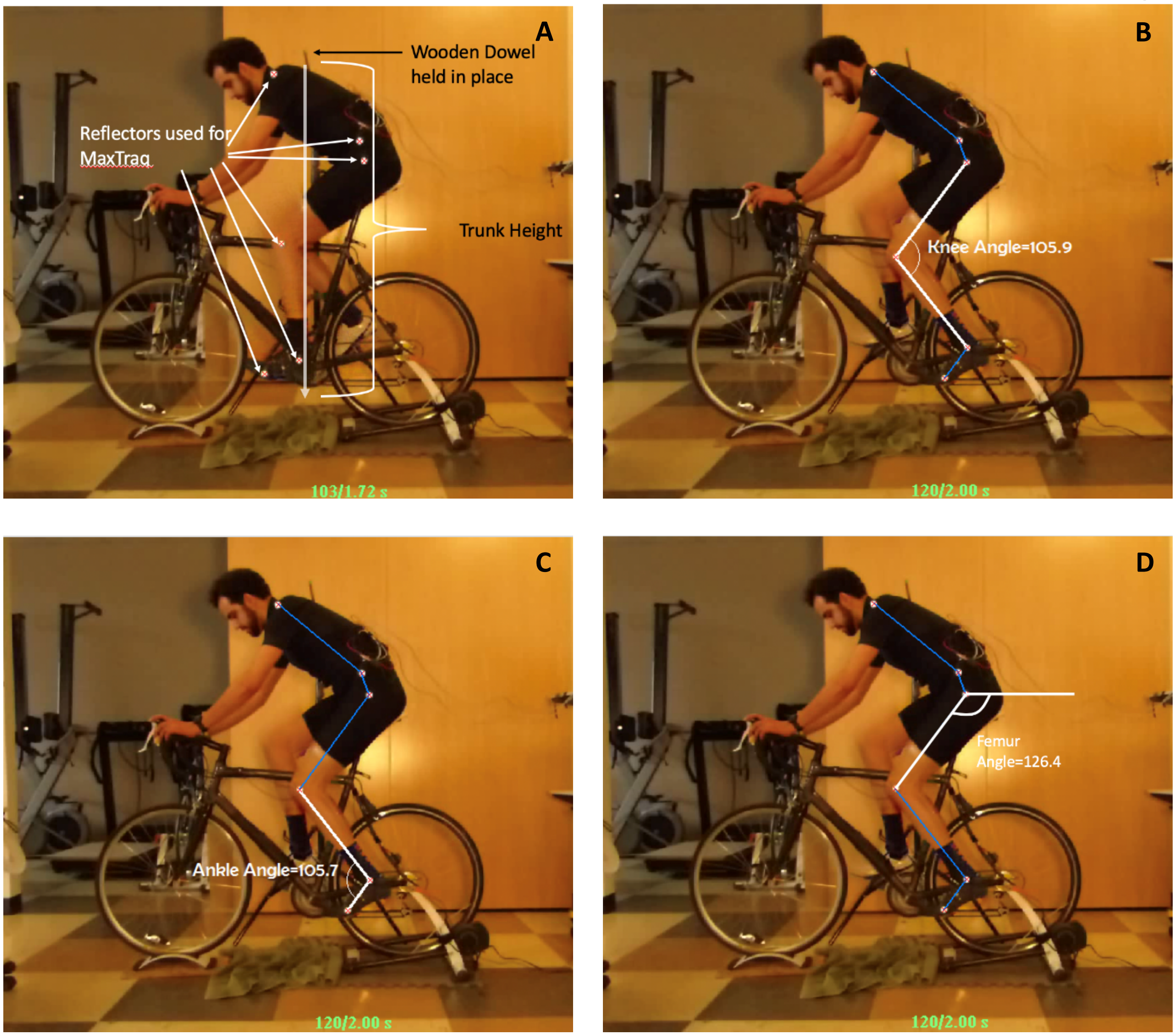

A
Wooden Dowel held in place
Reflectors used for MaxTraq
Trunk Height
103/1.72 s
B
Knee Angle=105.9
120/2.00 s
C
Ankle Angle=105.7
120/2.00 s
D
Femur Angle=126.4
120/2.00 s

Fig. 2

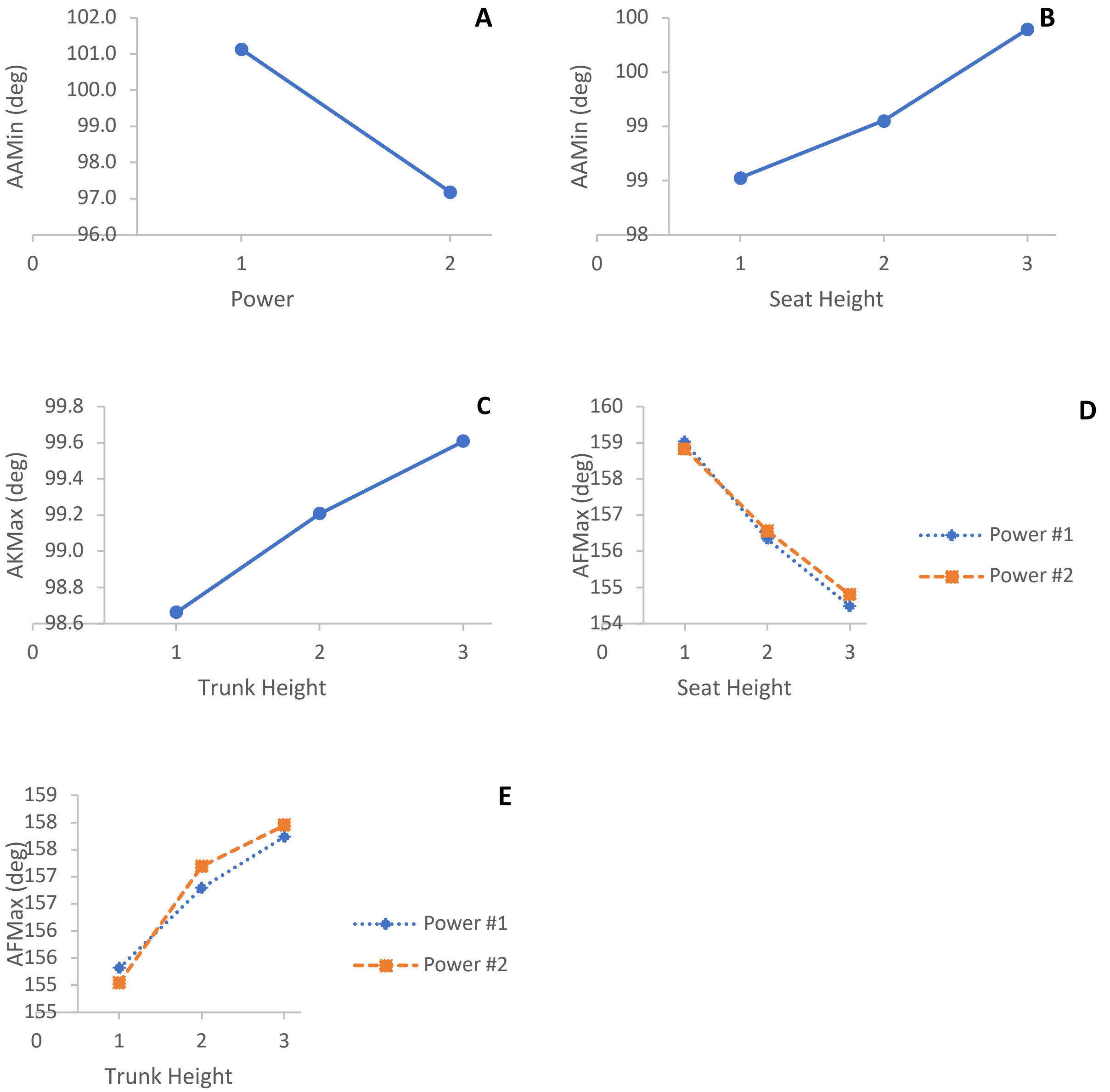

A
AAMin (deg)
Power
B
AAMin (deg)
Seat Height
C
AKMax (deg)
Trunk Height
D
AFMax (deg)
Seat Height
Power #1
Power #2
E
AFMax (deg)
Trunk Height
Power #1
Power #2

Fig. 3

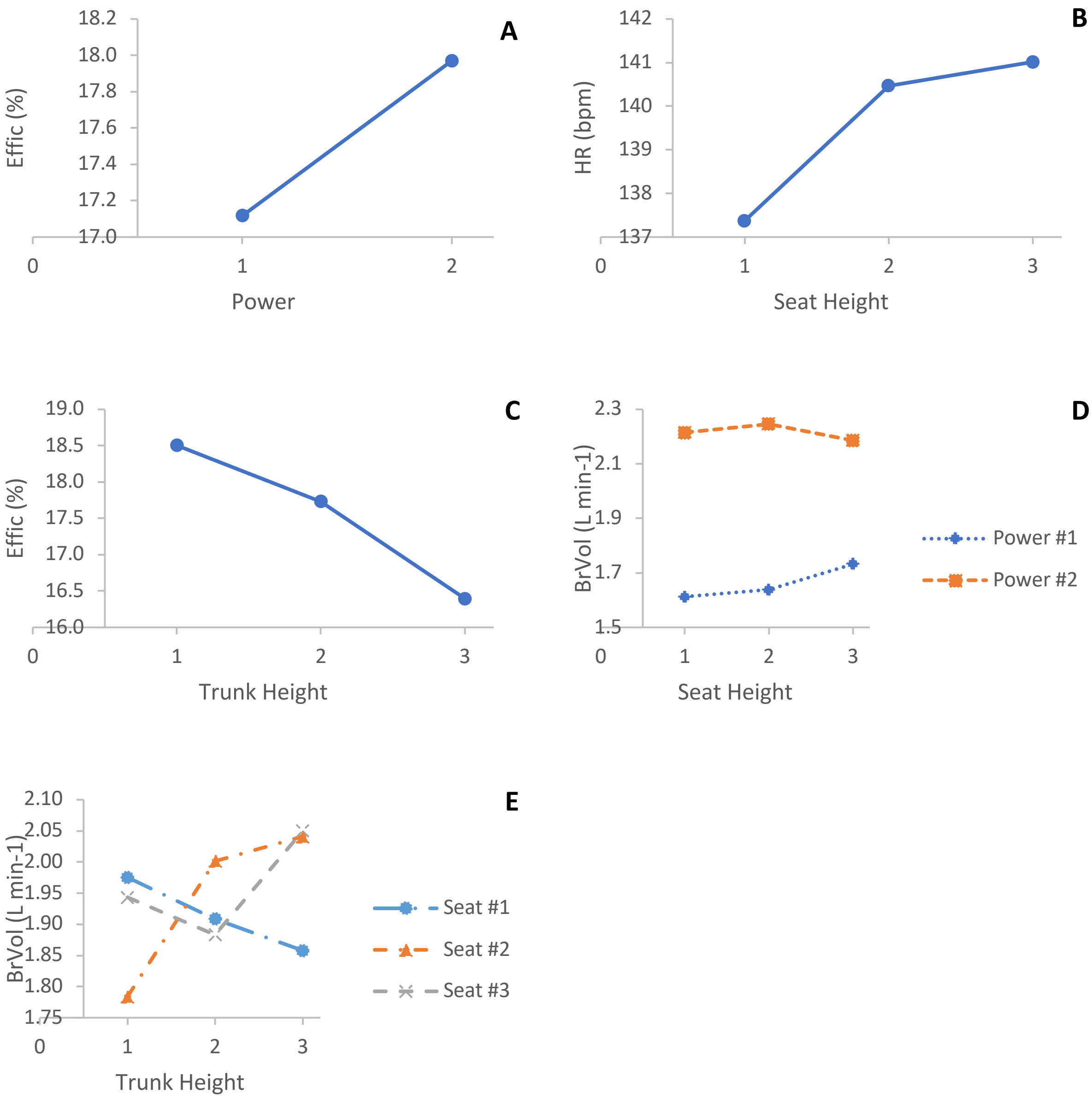

A
Effic (%)
18.2
18.0
17.8
17.6
17.4
17.2
17.0
0
1
2
Power
B
HR (bpm)
142
141
140
139
138
137
0
1
2
3
Seat Height
C
Effic (%)
19.0
18.5
18.0
17.5
17.0
16.5
16.0
0
1
2
3
Trunk Height
D
BrVol (L min-1)
2.3
2.1
1.9
1.7
1.5
0
1
2
3
Seat Height
Power #1
Power #2
E
BrVol (L min-1)
2.10
2.05
2.00
1.95
1.90
1.85
1.80
1.75
0
1
2
3
Trunk Height
Seat #1
Seat #2
Seat #3

Fig 4

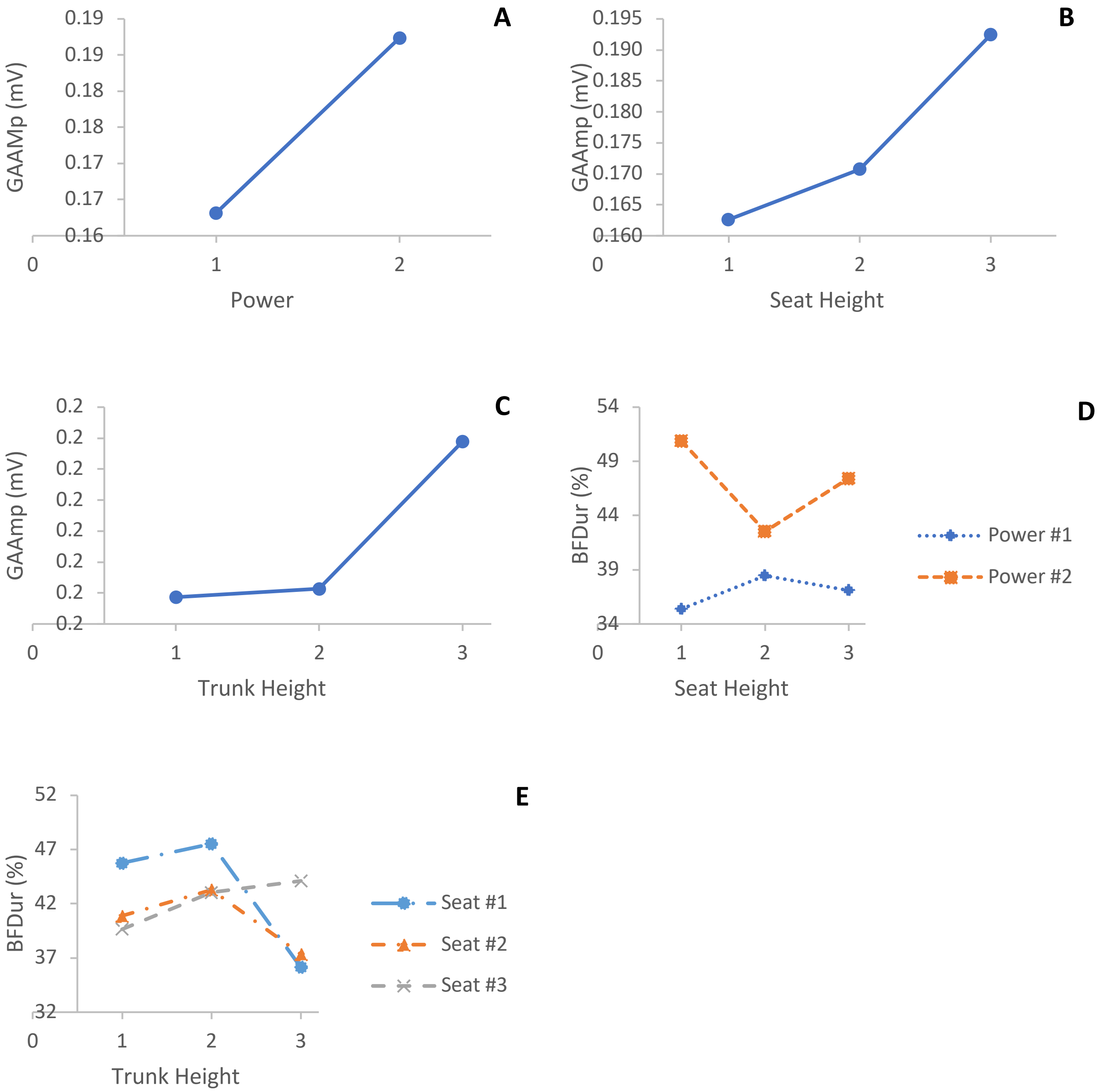

A
GAAMp (mV)
0.19
0.19
0.18
0.18
0.17
0.17
0.16
0
1
2
Power
B
GAAmp (mV)
0.195
0.190
0.185
0.180
0.175
0.170
0.165
0.160
0
1
2
3
Seat Height
C
GAAmp (mV)
0.2
0.2
0.2
0.2
0.2
0.2
0.2
0.2
0
1
2
3
Trunk Height
D
BFDur (%)
54
49
44
39
34
0
1
2
3
Seat Height
Power #1
Power #2
E
BFDur (%)
52
47
42
37
32
0
1
2
3
Trunk Height
Seat #1
Seat #2
Seat #3

Fig. 5

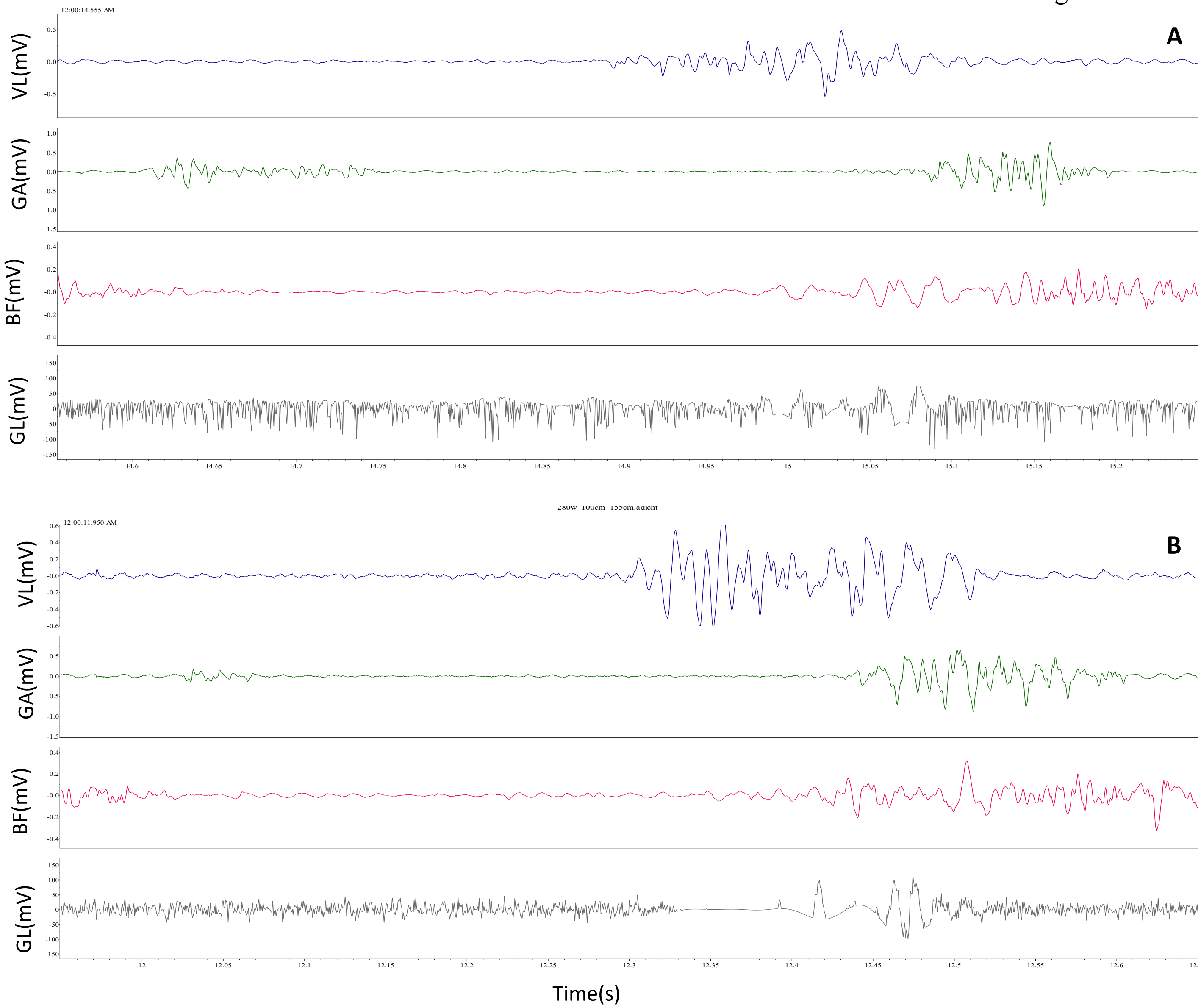


Fig. 6

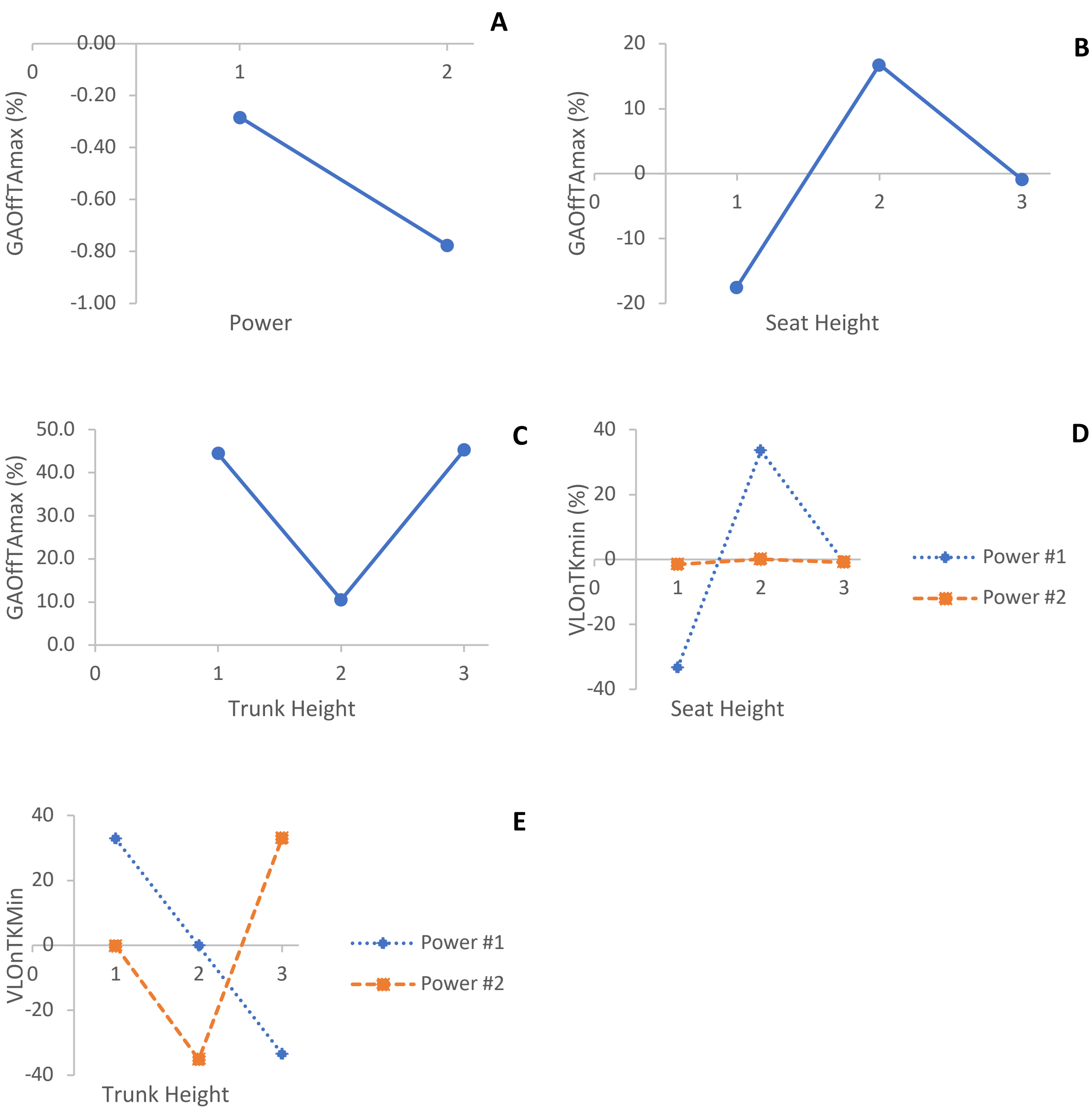
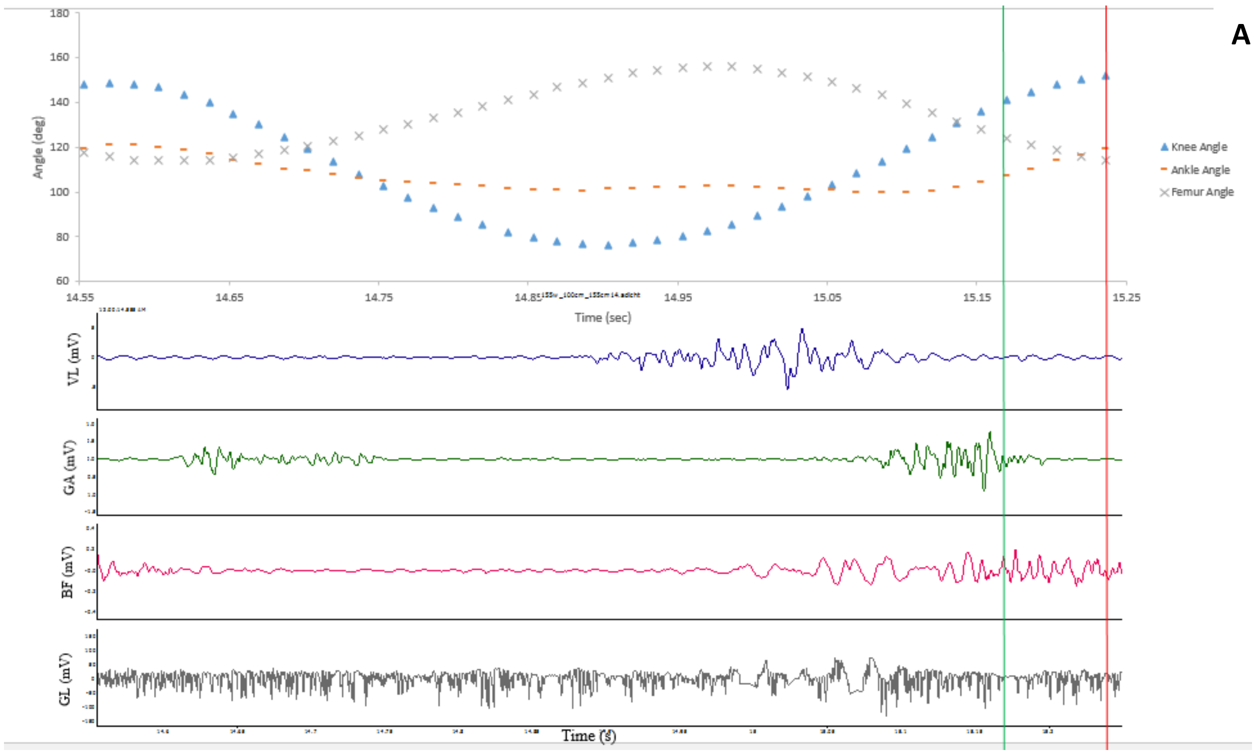
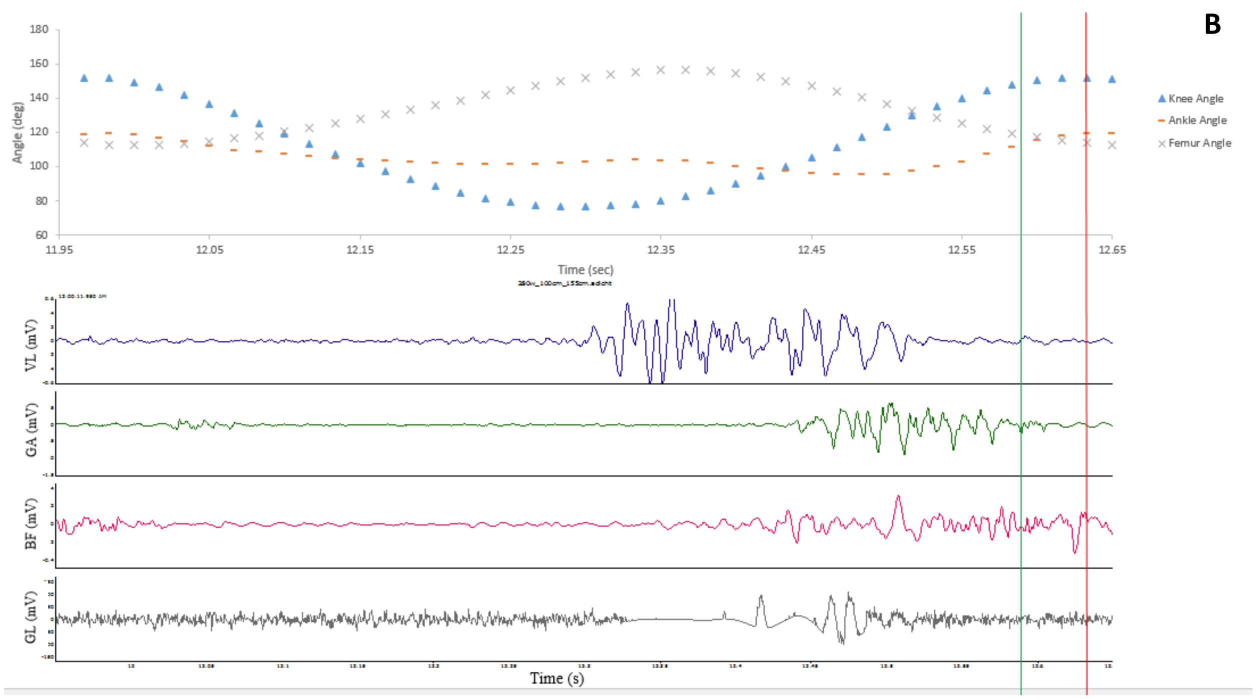

A
GAOffTAmax (%)
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
0
1
2
Power
B
GAOffTAmax (%)
20
10
0
-10
-20
1
2
3
Seat Height
C
GAOffTAmax (%)
50.0
40.0
30.0
20.0
10.0
0.0
0
1
2
3
Trunk Height
D
VLOnTKmin (%)
40
20
0
-20
-40
1
2
3
Seat Height
Power #1
Power #2
E
VLOnTKMin
40
20
0
-20
-40
1
2
3
Trunk Height
Power #1
Power #2

Fig. 7


A
Angle (deg)
180
160
140
120
100
80
60
14.55
14.65
14.75
14.85
14.95
15.05
15.15
15.25
Time (sec)
Knee Angle
Ankle Angle
Femur Angle
VL (mV)
GA (mV)
BF (mV)
GL (mV)
Time (s)


B
Angle (deg)
180
160
140
120
100
80
60
11.95
12.05
12.15
12.25
12.35
12.45
12.55
12.65
Time (sec)
Knee Angle
Ankle Angle
Femur Angle
VL (mV)
GA (mV)
BF (mV)
GL (mV)
Time (s)