Author(s): Huang, Yangjian; Xia, Haisheng; Chen, Gang; Cheng, Sulin; Cheung, Roy T.H.; Shull, Peter B.

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Foot Strike Pattern, Step Rate, and Trunk Posture Combined Gait Modifications to Reduce Impact Loading during Running

Running Title: Foot strike pattern, step rate, and trunk posture to reduce impact loading

Yangjian Huang [a], Haisheng Xia [a], Gang Chen [b], Sulin Cheng [c, d], Roy T.H. Cheung [e], Peter B. Shull [a]

[a] *State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*

[b] *Department of Physical Education, Shanghai Jiao Tong University, Shanghai 200240, China*

[c] *Exercise Health and Technology Center, Department of Physical Education, Shanghai Jiao Tong University, Shanghai 200240, China*

[d] *Department of Health Sciences, University of Jyväskylä, Jyväskylä 40014, Finland*

[e] *Gait & Motion Analysis Laboratory, Department of Rehabilitation Sciences, Hong Kong Polytechnic University, Hung Hom, Hong Kong*

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Corresponding Author: Peter B. Shull

Room 930, Mechanical Engineering Bld. A, School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Shanghai 200240, China, Email: pshull@sjtu.edu.cn

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ABSTRACT

Elevated impact loading can be detrimental to runners as it has been linked to the increased risk of tibial stress fracture and plantar fasciitis. The objective of this study was to investigate the combined effects of foot strike pattern, step rate, and anterior trunk lean gait modifications on impact loading in runners. Nineteen healthy runners performed 12 separate gait modification trials involving: three foot strike patterns (rearfoot, midfoot, and forefoot strike), two step rates (natural and 10% increased), and two anterior trunk lean postures (natural and 10-degree increased flexion). Overall, forefoot strike combined with increased step rate led to the lowest impact loading rates, and rearfoot strike combined with anterior trunk lean led to the highest impact loading rates. In addition, there were interaction effects between foot strike pattern and step rate on awkwardness and effort, such that it was both more natural and easier to transition to a combined gait modification involving forefoot strike and increased step rate than to an isolated gait modification involving either forefoot strike or increased step rate. These findings could help to inform gait modifications for runners to reduce impact loading and associated injury risks.

INTRODUCTION

Running is a popular sport with an estimated 18 million runners in the US alone (Running USA), however running can result in overuse injuries (Knobloch et al., 2008). Tibial stress fractures are particularly widespread (Fredericson and Misra, 2007; Matheson et al., 1987; Milgrom et al., 2003; Taunton et al., 2002) and are one of the most common overuse injuries in both civilian runners and military recruits (Jacobs et al., 2014). Repetitive submaximal loading is believed to be the key mechanical risk factor in the development of stress fractures (Pegrum et al., 2014; Van Der Worp et al., 2016).

Elevated loading rates are closely related to tibial stress fractures development. Milner et al. (2006) observed that runners who had sustained a tibial stress fracture exhibited significantly greater impact loading rates as compared with healthy controls. Vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR) are higher in runners who have sustained a stress fracture as compared with healthy controls (Van Der Worp et al., 2016; Zadpoor and Nikooyan, 2011), and the same phenomenon has been observed for runners with plantar fasciitis (Pohl et al., 2009), patellofemoral pain (Cheung and Davis, 2011), and chronic exertional compartment syndrome (Diebal et al., 2012, 2011). Greater VALR and VILR could be caused by increased vertical body stiffness during landing (Hunter, 2003; McMahon and Cheng, 1990). The increased vertical stiffness thus increases the chance of injury because it reduces shock attenuation and correspondingly increases peak forces (Chan et al., 2018). Similarly, vertical impact peak (VIP) has been linked to running injuries including retrospective tibial stress fractures (Blackmore et al., 2016; Zifchock et al., 2006). Peak tibial acceleration (PTA) has also been identified as a biomechanical predictor of tibial stress fractures in runners (Milner et al., 2007, 2006).

Therefore, running gait modifications that lower loading rates can potentially reduce the risk of injury (Chan et al., 2018; Crowell et al., 2010; Crowell and Davis, 2011; Giandolini et al., 2013b; Hafer et al., 2015; Laughton et al., 2003; Wood and Kipp, 2014). Foot strike pattern, step rate, and anterior trunk lean are three potential gait modification strategies for reducing loading rates while running. Altering foot strike pattern can reduce impact loading, specifically, forefoot and midfoot strike results in lower PTA (Cheung et al., 2017; Crowell and Davis, 2011), joint force (Kulmala et al., 2013; Lieberman et al., 2010; Warne et al., 2014), vertical impact peak and loading rates (Cheung and Davis, 2011; Diebal et al., 2012, 2011; Lieberman, 2012), and medial compartment tibiofemoral joint loading (Bowersock et al., 2017), which may in turn lead to reduced running injury rates (Daoud et al., 2012). Step rate manipulation is another running adaptation linked to loading rates (Hobara et al., 2012). Previous studies have reported that increasing step rate can lead to a reduction in vertical loading rates (Hafer et al., 2015), mechanical energy absorbed by the hip and knee joints (Heiderscheit et al., 2011), and the risk of stress fractures (Edwards et al., 2009). Anterior trunk lean is also commonly suggested as a gait modification to soften footfalls (Arendse et al., 2004) and was originally proposed by Romanov in the Pose Method (Fletcher et al., 2008). While fewer studies have been performed investigating the relationship between anterior trunk lean and impact loading, it has been shown that knee joint energetics (Arendse et al., 2004; Teng and Powers, 2014a), knee muscles activity (Teng and Powers, 2016), and patellofemoral joint stress (Teng and Powers, 2014b) are linked to anterior trunk lean in runners.

While current research approaches typically examine the effects of a single gait modification, the combination of multiple simultaneous gait modifications could reveal greater benefits and deeper insights. Hence, the purpose of this study was to examine the effect of foot strike pattern, step rate, and anterior trunk lean gait modifications on impact loading in runners. We hypothesized that there would be at least one combination of multiple simultaneous gait modifications that would reduce loading rates more than any single gait modification.

METHODS

A. Participants

Nineteen male healthy runners were recruited in this study (age: 21.74±2.64 years, height: 178.84±5.43 cm, weight: 68.48±6.28 kg, weekly running mileage: 17.92±10.15 km) from local running clubs. They were all habitual shod runners (a minimum running mileage of 10 km per week for at least 6 months). Participants were excluded if they had any active injuries or conditions that would affect their gait and running mechanics. We also excluded participants with any lower limb or back surgery, or any cognitive impairment that would inhibit motor learning. Participants receiving any other concurrent gait retraining during the study period were excluded as well. All the participants provided written informed consent before being tested and the experimental procedure was reviewed and approved by the university ethics committee (ml2018022). Among participants, there were 15 midfoot strikers and 4 rearfoot strikers. The mean baseline strike index of participants was 38.7±9.0. The mean baseline step rate was 173.1±16.0 steps/minute, and the mean baseline anterior trunk lean was 18.8±3.6 deg.

B. Experimental protocol

Reflective markers were placed at specific body landmarks according to the modified Plug-in Gait lower body model (Bonnechere et al., 2015). Marker trajectory were collected using a motion capture system (Vicon, Oxford, UK) with sixteen cameras operating at 100 Hz. Synchronized ground reaction force data were measured using an instrumented treadmill (Bertec, Columbus, OH, USA) at 1,000 Hz. An inertial measurement unit (Xsens MTI300, Xsens North America Inc., CA, USA) was securely affixed onto the anteromedial aspect of distal right tibia and the x-axis was aligned with the longitudinal direction of tibia to record PTA (Crowell et al., 2010; Crowell and Davis, 2011) at 1,000 Hz.

Participants first performed standardized warm-up exercise to become familiar with the treadmill running at different speeds. They were then asked to run with their usual shoes on a self-paced instrumented treadmill (Bertec, Columbus, OH, USA) for five minutes which was baseline trial. In order to eliminate speed and footwear effects, test running speed and shoe condition were kept constant within each participant for all subsequent trials. This baseline trial was post processed immediately to determine each participant's baseline running parameters and set the target anterior trunk lean and increased step rate for subsequent gait modification trials. The baseline trial is one of the twelve possible gait combinations.

Before gait modification trials began, each participant performed a 2-minute practice trial (Bowersock et al., 2017) to become familiar with the visual and audio feedback (Fig. 1). Then each participant performed the remaining 11 additional combination gait patterns after the baseline trial, i.e., three foot strike patterns (rearfoot, midfoot, and forefoot strike), two step rates (natural and 10% increased), and two anterior trunk lean postures (natural and 10-degree increased anterior lean). Specific thresholds for increased step rate and increased anterior trunk lean were based on the findings reported in previous studies (Bowersock et al., 2017; Hafer et al., 2015; Teng and Powers, 2014b, 2014a). The trial sequence was randomized, and participants ran for five minutes during each trial while receiving visual feedback and audio cues (Fig. 1). Participants rested for five minutes or longer if requested between each trial.

Strike index was computed in real time via a customized Matlab program (The Mathworks Inc, Natick, MA, USA) and was calculated as a measurement of the initial center of pressure (COP) position relative to the foot length (Cavanagh and Lafortune, 1980). A digital audio metronome (Seiko sq70, Seiko, Singapore) was used to prompt the appropriate step rate (Heiderscheit et al., 2011). Each participant was asked to match his footfalls to the designated tempo of the metronome while running. We confirmed successful adaptation of the prescribed step rate by visual inspection (Heiderscheit et al., 2011). Anterior trunk lean was also computed in real time via the customized Matlab program as the intercept angle between the trunk and the pelvis segments in the sagittal plane (Teng and Powers, 2014b).

Specific gait modifications were trained via real-time visual feedback for target foot strike patterns and trunk postures and audio cues for target step rates (Fig. 1). The monitor for visual feedback was placed approximately 1.5 m in front of the treadmill. Participants were instructed to modify their foot strike pattern and trunk posture such that the blue circle, indicating the current step, moved within the yellow rectangle, indicating the target parameters. Concurrently, participants were instructed to match their step rate with the tempo of metronome. A test facilitator monitored the modifications while standing next to the treadmill and gave general oral instructors and encouragement to adjust the gait pattern as needed.

Subjective data was also recorded at the end of each running trial to determine awkwardness and effort. Each participant rated the awkwardness of the running gait on a 10 cm visual analog scale, with 0 corresponding to completely natural and 10 being maximally awkward (Barrios et al., 2010). Participants also rated their perception of effort required to execute the modified pattern on a 10 cm visual analog scale, 0 corresponding to effortless execution and 10 indicating maximal effort.

C. Data processing

Marker data were post processed and filtered at 8 Hz (cut-off frequency) and force and acceleration data at 50 Hz with a forth order, recursive, Butterworth, low pass filter (Crowell and Davis, 2011). PTA was calculated as the peak tibial acceleration after initial contact from the x-axis of the inertial measurement unit aligned with the longitudinal direction of the tibia. Vertical loading variables were computed based on previously established methods (An et al., 2015; Cheung and Rainbow, 2014; Milner et al., 2006; Zhang et al., 2017). Specifically, VIP was identified as the impact transient that was generated when foot first contacted the ground. In case of an absence of an initial vertical impact peak, the value of 13% of stance was used as a surrogate for time to vertical impact peak (Blackmore et al., 2016). VALR was the slope of the line through the 20% point and the 80% point of the VIP. VILR was the maximum slope of the vertical ground reaction force curve between successive data points in the same region. For all trials, marker, force plate, and tibial acceleration data were collected. Subjective scores including awkwardness and effort were collected after each trial. During post data processing, all data were extracted from the first 20 step window in which at least 15 steps met all the target gait modification parameters. Five minutes was selected as the running time to ensure all runners had sufficient time to adopt and maintain the target gait for a 20 step window. Post-processing computation was performed using customized Matlab software.

Three-way repeated measures ANOVA was used to compare the influence of strike index, anterior trunk lean, and step rate, on VALR, VILR, VIP, PTA, awkward score, and effort score for all gait modifications. When main effects were significant, post hoc pairwise comparison with bonferroni corrections were conducted to compare specific pairs of gait modifications. Statistical analyses were conducted using SPSS (SPSS, IBM, Armonk, NY, USA), and the significance level was set to $p < 0.05$.

RESULTS

Overall, participants were able to successfully adopt the various combined gait modifications, and there were distinct separations between forefoot, midfoot, and rearfoot patterns, between baseline and increased step rates, and between baseline and anterior trunk lean (Fig. 2). For statistically comparing VALR, VILR, VIP, PTA, Awkwardness, and Effort between all gait combinations (Figure 3 and 4), we have included six appendix tables (Appendix Tables 1-6) showing p-values for comparisons of each pair of gait combinations. Forefoot strike pattern with increased step rate was the gait combination that led to the lowest loading rates, and rearfoot strike with anterior trunk lean was the gait combination that led to the highest loading rates (Fig. 3, Appendix Tables 1, 2, and 4). Participants most preferred running with midfoot strike, baseline step rate, and baseline trunk lean as evidenced by rating this gait combination as the least awkward and least effortful (Fig. 4, Appendix Tables 5 and 6). Participants least preferred running with rearfoot strike, increased step rate, and anterior trunk lean as evidenced by rating this gait combination the most awkward and most effortful (Fig. 4, Appendix Tables 5 and 6). There were differences among gait combinations for VALR, VILR, and PTA, and no difference for VIP (Fig. 3, Appendix Tables 1-4).

Isolating individual gait modifications showed that forefoot strike had lower VALR and VILR compared to midfoot strike and rearfoot strike (Table 1). We did not find differences for VALR and VILR between midfoot strike and rearfoot strike, and there was no difference among VIP and PTA values under different foot strike patterns. Midfoot strike had lower awkwardness and effort scores than forefoot and rearfoot strike, and forefoot strike had lower awkwardness and effort scores than rearfoot strike. Increased step rate had lower VALR compared to baseline step rate, while no differences for VILR, VIP, and PTA between baseline and increased step rate were found (Table 2). Baseline step rate had lower awkwardness and effort scores than increased step rate. Baseline trunk lean had lower VALR and VILR compared to anterior trunk lean, and lower awkwardness and effort scores than anterior trunk lean (Table 3).

There was an interaction effect from the combination of foot strike patterns and step rates on awkwardness and effort (Appendix Table 7). This indicates that when running with a higher step rate, participants would not feel a difference in awkwardness and effort when transitioning to a forefoot strike pattern. However, when running with a baseline step rate, participants would feel a difference. There was also an interaction effect from the combination of all three factors on effort (Appendix Table 7). This shows that anterior trunk lean increases the amount of effort during the transition to forefoot strike with higher step rate as compared to the baseline trunk lean condition. There were no interaction effects between foot strike pattern, trunk lean posture or step rate on VALR, VILR, VIP, and PTA.

DISCUSSION

This study investigated the effect of foot strike pattern, step rate, and anterior trunk lean gait modifications on reducing impact loading in runners. In support of our hypothesis, simultaneous gait modifications reduced impact loading rates more than any single gait modification. The specific gait modification combination was forefoot strike and increased step rate. To our best knowledge, this is the first study to systematically modify three gait parameters in runners and investigate the related effect on impact loading. Dos Santos et al. (2016) examined the effect of forefoot striking pattern, increased step rate, and increased anterior trunk lean on the ankle, knee, hip, and trunk kinematics for reducing the risk of patellofemoral pain. Bowersock et al. (2017) examined step length and foot strike pattern's effect on tibiofemoral joint kinetics during running and recommended a combination of a shorter step length and forefoot strike pattern to reduce peak medial compartment contact forces. Yong et al. (2018) examined training runners to forefoot strike without changing step rate and to increase step rate without changing foot strike pattern, finding that both individual modifications may reduce the risk of tibial stress fractures. Others have performed walking gait studies involving simultaneous gait parameter changes to reduce the knee adduction moment (Favre et al., 2016; Shull et al., 2011). The results of this study also demonstrated that it is feasible to train three gait parameters simultaneously by using two dimensional visual feedback and a periodic audio cue in contrast to previous approaches using either no feedback, self-selected changes (Favre et al., 2016) or all haptic feedback (Shull et al., 2011). It is also possible that the combined forefoot and increased step rate modification might be similar to forefoot strike interventions in cases when step rate is not controlled.

The decrease in impact loading rates via forefoot strike and increased step rate suggest that tibial stress fracture related risk indicators can be reduced by this running gait modification combination. Also, there was no interaction between forefoot strike and increased step rate on loading rates, which means that these two modifications independently reduce loading rates and thus the combination of both appears to have a cumulative summing effect to reduce the loading rates, which is consistent with previous results (Bowersock et al., 2017). In addition, the interaction effect from the combination of foot strike pattern and step rate on awkwardness and effort also shows that it is easier to transfer to forefoot strike pattern when the step rate can be increased at the same time rather than keeping the step rate at the baseline level. Thus, combining forefoot strike and increased step rate not only reduces loading rates to mitigate the risk of tibial stress fractures but also makes the transition easier than changing to forefoot strike or increased step rate independently, thus making participants more likely to adapt to and persist with the new gait pattern.

Changes in foot strike patterns found in this study largely align with previous work. In our study, VALR decreased for forefoot strike compared to non-fore foot strike as has been reported in several previous studies (An et al., 2015; Bowersock et al., 2017; Chen et al., 2016; Cheung and Davis, 2011; Cheung and Rainbow, 2014; Giandolini et al., 2013a; Kulmala et al., 2013; Shih et al., 2013; Yong et al., 2018). We also found no difference in VALR between midfoot and rearfoot strike pattern which aligns with similar findings (Giandolini et al., 2013b; Laughton et al., 2003). For VILR, we found that forefoot strike was lower compared to non-fore foot strike, but that there was no difference between midfoot strike and rearfoot strike, which is consistent with the reductions reported (An et al., 2015; Boyer et al., 2014; Chen et al., 2016; Cheung and Davis, 2011; Shih et al., 2013) and no difference previously reported (Cheung and Rainbow, 2014; Laughton et al., 2003). In our study, we did not find any difference in VIP or PTA when changing foot strike patterns, and this phenomenon has similarly been reported in previous studies (Bowersock et al., 2017; Giandolini et al., 2013b; Yong et al., 2018). For the result that all rearfoot strike combinations are ranked high for awkwardness and effort, the likely reason is modification to clean rearfoot strike pattern was actually hard especially when accomplished together with changing of step rate and trunk posture. During the gait modification related to rearfoot strike, we instructed participants to try their best to move their COP backward to drive the blue circle into the lower part of lowest square representing rearfoot strike pattern and we instructed the lower the better, achieving pure rearfoot strike pattern. We found that it is easier for subjects to move the COP forward compared to moving it backward. Because most of our participants are midfoot strikers, they did four combinations involving rearfoot strike pattern.

In this study increased step rate led to lower VALR, which aligns with previous studies reporting decreased impact loading with increased step rate (Bowersock et al., 2017; Heiderscheit et al., 2011; Hobara et al., 2012; Morin et al., 2007; Willy et al., 2016). Also, no difference was found in VILR and VIP between step rate conditions, which is consistent with findings in previous studies (Giandolini et al., 2013a; Hafer et al., 2015; Yong et al., 2018). Increasing step rate did not lower PTA, which is also consistent with previous findings (Yong et al., 2018).

Results also showed that the anterior trunk lean increased loading rates and increased awkwardness and effort. The interaction effect from the combination of foot strike pattern, step rate, and trunk lean on effort demonstrates the modification of trunk posture at the same time is an extra burden to runners when modifying foot strike pattern and step rate together. In previous work, Teng et al. (2014b) reported that lower patellofemoral joint stress and reaction force resulted from flexed sagittal plane trunk postures, however our study shows that anterior trunk lean posture would also incur higher impact loading rates, which may mitigate the improvement of patellofemoral pain (Cheung and Davis, 2011). Knee joint energetics and loading could also be decreased with flexed trunk posture but it would demand higher hip energy (Arendse et al., 2004; Teng and Powers, 2016, 2014a). Thus, running gait modifications requiring increased anterior trunk lean should carefully consider the potential secondary effect of increased impact loading.

A limitation of our study was that we only tested runners during a single session. Further investigation should be performed to determine long-term learning and adaption effects with multiple training session and extended follow up tests. Also, only male participants were tested, and given that there are documented gender differences in the biomechanics of gaits (Cho et al., 2004; Ferber et al., 2003), further research is needed to explore the effects of combinational gait modifications on female runners. Another potential limitation of this study is that, while loading rates were computed based on previously established methods, newer alternative methods for calculating loading rates (Yong et al., 2018) could potentially lead to different or more insightful results. While forefoot strike with increased step rate modification can decrease the impact loading rates, there are certain potential risks that need to be considered with such a gait modification such as a parallel increase in ankle plantarflexor and increased achilles tendon loading may increase the risk of ankle and foot injuries (Almonroeder et al., 2013; Kulmala et al., 2013). Future work should also focus on the best way to train new combination of gait modifications to best minimize awkwardness and effort to increase runner comfort and performance.

In conclusion, we examined the effect of a combination of gait modifications on impact loading for runners. Forefoot strike combined with increased step rate reduced impact loading rates the most effectively. These results could broadly benefit runners given that lower impact loading is closely related to tibial stress fractures, plantar fasciitis, patellofemoral pain, and chronic exertional compartment syndrome etc. These finding could thus serve as a foundation to help inform and prescribe gait modifications for runners.

CONFLICT OF INTEREST

None of the authors had any conflict of interest regarding this manuscript.

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CAPTIONS

Fig. 1 Typical subject running on the treadmill (left) while receiving real-time visual biofeedback to inform foot strike pattern and trunk lean posture (right) and a metronome to inform step rate. For visual biofeedback (right), the vertical axis indicates the required foot strike pattern (FSP), bottom: rearfoot strike, middle: midfoot strike, and top: forefoot strike. The horizontal axis indicates the required anterior trunk lean angle, left: baseline and right: 10-degree increased.

Fig. 2 Strike index, step rate, and trunk lean angle for 12 gait combinations. Bars indicate averaged ± one standard deviation. Blue represents forefoot strike pattern, green represents midfoot strike pattern, red represents rearfoot strike pattern. Dots represent increased step rate. Slashes represent anterior trunk lean.

Fig. 3 Impact loading rates (VALR, VILR, VIP) and peak tibial acceleration (PTA) for 12 gait combinations. Bars indicate averaged ± one standard deviation. Blue represents forefoot strike pattern, green represents midfoot strike pattern, red represents rearfoot strike pattern. Dots represent increased step rate. Slashes represent anterior trunk lean. More comparison results can be found in appendix Table 1-4.

Fig. 4 Runner subjective feedback (awkwardness and effort) for 12 gait combinations. Bars indicate averaged ± one standard deviation. Blue represents forefoot strike pattern, green represents midfoot strike pattern, red represents rearfoot strike pattern. Dots represent increased step rate. Slashes represent anterior trunk lean. More comparison results can be found in Appendix Table 5-6.

Table. 1 Impact loading rates (VALR, VILR, VIP), peak tibial acceleration (PTA), awkwardness and effort ratings between forefoot, midfoot, and rearfoot strike. Results are reported as mean ± one standard deviation. Bold values indicate a significant difference of $p < 0.05$.

Table. 2 Impact loading rates (VALR, VILR, VIP), peak tibial acceleration (PTA), awkwardness and effort ratings between baseline and increased step rate condition. Results are reported as mean ± one standard deviation. Bold values indicate a significant difference of $p < 0.05$.

Table. 3 Impact loading rates (VALR, VILR, VIP), peak tibial acceleration (PTA), awkwardness and effort ratings between baseline and anterior trunk lean condition. Results are reported as mean ± one standard deviation. Bold values indicate a significant difference of $p < 0.05$.

Appendix Table. 1 P-values for comparisons of each pair of gait combinations for vertical average loading rate (VALR). FFS, MFS, and RFS represent forefoot, midfoot, and rearfoot strike respectively. NSR, HSR represents baseline and higher increased step rate. NTL, ATL represents baseline and anterior trunk lean. Bold values indicate a significant difference of $p < 0.05$.

Appendix Table. 2 P-values for comparisons of each pair of gait combinations for vertical instantaneous loading rate (VILR). FFS, MFS, and RFS represent forefoot, midfoot, and rearfoot strike respectively. NSR, HSR represents baseline and higher increased step rate. NTL, ATL represents baseline and anterior trunk lean. Bold values indicate a significant difference of $p < 0.05$.

Appendix Table. 3 P-values for comparisons of each pair of gait combinations for vertical impact peak (VIP). FFS, MFS, and RFS represent forefoot, midfoot, and rearfoot strike respectively. NSR, HSR represents baseline and higher increased step rate. NTL, ATL represents baseline and anterior trunk lean. Bold values indicate a significant difference of $p < 0.05$.

Appendix Table. 4 P-values for comparisons of each pair of gait combinations for peak tibial acceleration (PTA). FFS, MFS, and RFS represent forefoot, midfoot, and rearfoot strike respectively. NSR, HSR represents baseline and higher increased step rate. NTL, ATL represents baseline and anterior trunk lean. Bold values indicate a significant difference of $p < 0.05$.

Appendix Table. 5 P-values for comparisons of each pair of gait combinations for awkwardness. FFS, MFS, and RFS represent forefoot, midfoot, and rearfoot strike respectively. NSR, HSR represents baseline and higher increased step rate. NTL, ATL represents baseline and anterior trunk lean. Bold values indicate a significant difference of $p < 0.05$.

Appendix Table. 6 P-values for comparisons of each pair of gait combinations for effort. FFS, MFS, and RFS represent forefoot, midfoot, and rearfoot strike respectively. NSR, HSR represents baseline and higher increased step rate. NTL, ATL represents baseline and anterior trunk lean. Bold values indicate a significant difference of $p < 0.05$.

Appendix Table. 7 P-values for interaction effect of foot strike pattern, step rate, and anterior trunk lean on vertical average loading rate (VALR), vertical instantaneous loading rate (VILR), vertical impact peak (VIP), peak tibial acceleration (PTA), Awkwardness, and Effort. FSP represents foot strike pattern, SR represents step rate, and TL represents anterior trunk lean. Bold values indicate a significant difference of $p < 0.05$.

Figure 1

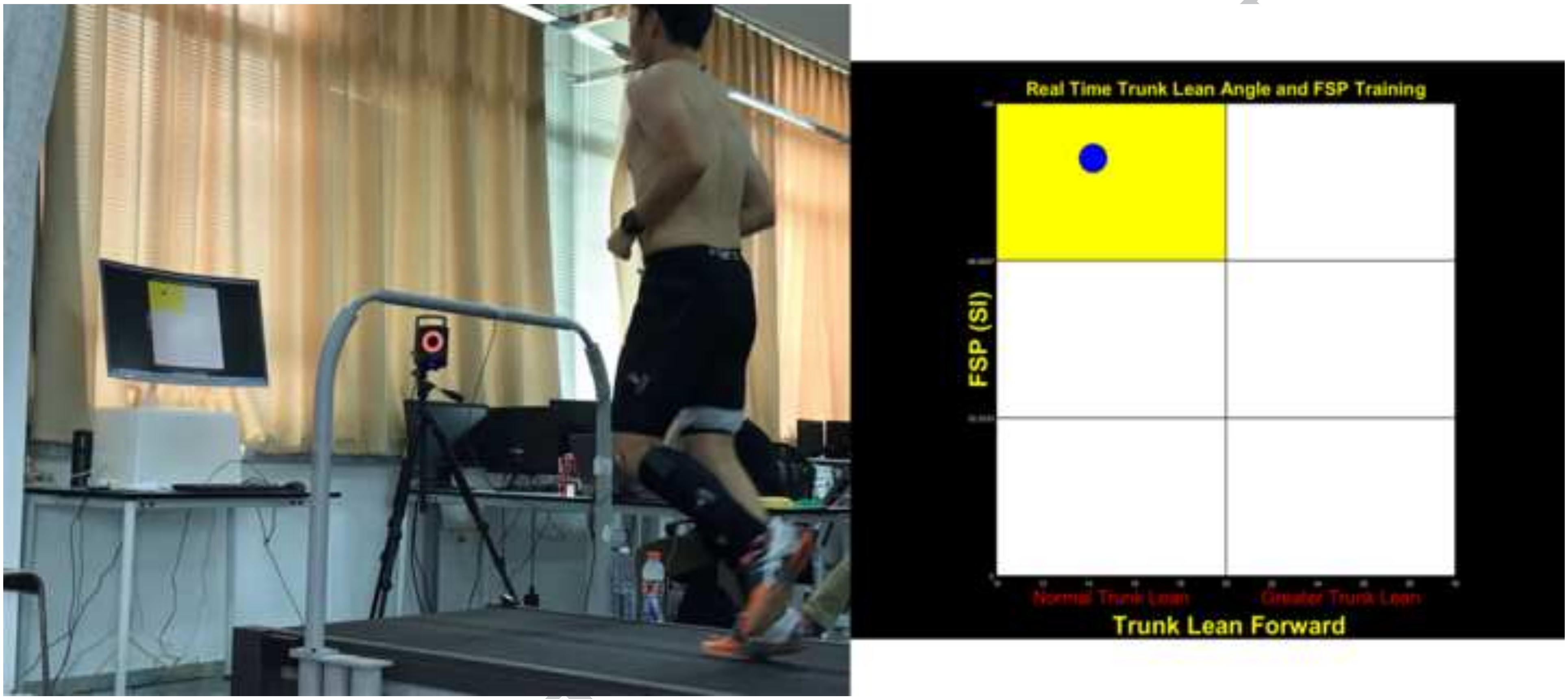
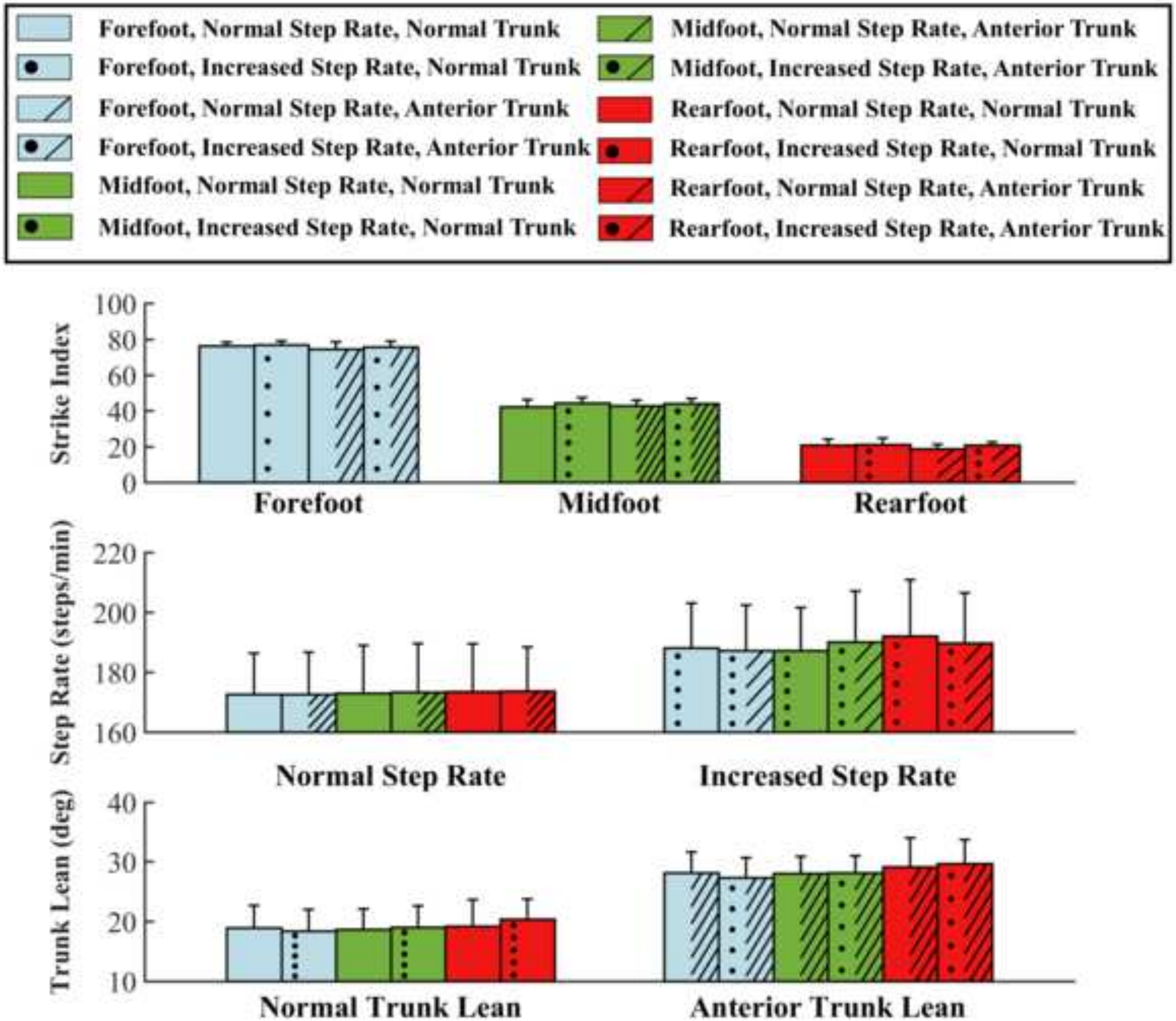

Real Time Trunk Lean Angle and FSP Training
FSP (SI)
Normal Trunk Lean
Greater Trunk Lean
Trunk Lean Forward

Figure 2



Forefoot, Normal Step Rate, Normal Trunk
Forefoot, Increased Step Rate, Normal Trunk
Forefoot, Normal Step Rate, Anterior Trunk
Forefoot, Increased Step Rate, Anterior Trunk
Midfoot, Normal Step Rate, Normal Trunk
Midfoot, Increased Step Rate, Normal Trunk
Midfoot, Normal Step Rate, Anterior Trunk
Midfoot, Increased Step Rate, Anterior Trunk
Rearfoot, Normal Step Rate, Normal Trunk
Rearfoot, Increased Step Rate, Normal Trunk
Rearfoot, Normal Step Rate, Anterior Trunk
Rearfoot, Increased Step Rate, Anterior Trunk
Strike Index
100
80
60
40
20
0
Forefoot
Midfoot
Rearfoot
Step Rate (steps/min)
220
200
180
160
Normal Step Rate
Increased Step Rate
Trunk Lean (deg)
40
30
20
10
Normal Trunk Lean
Anterior Trunk Lean

Figure 3

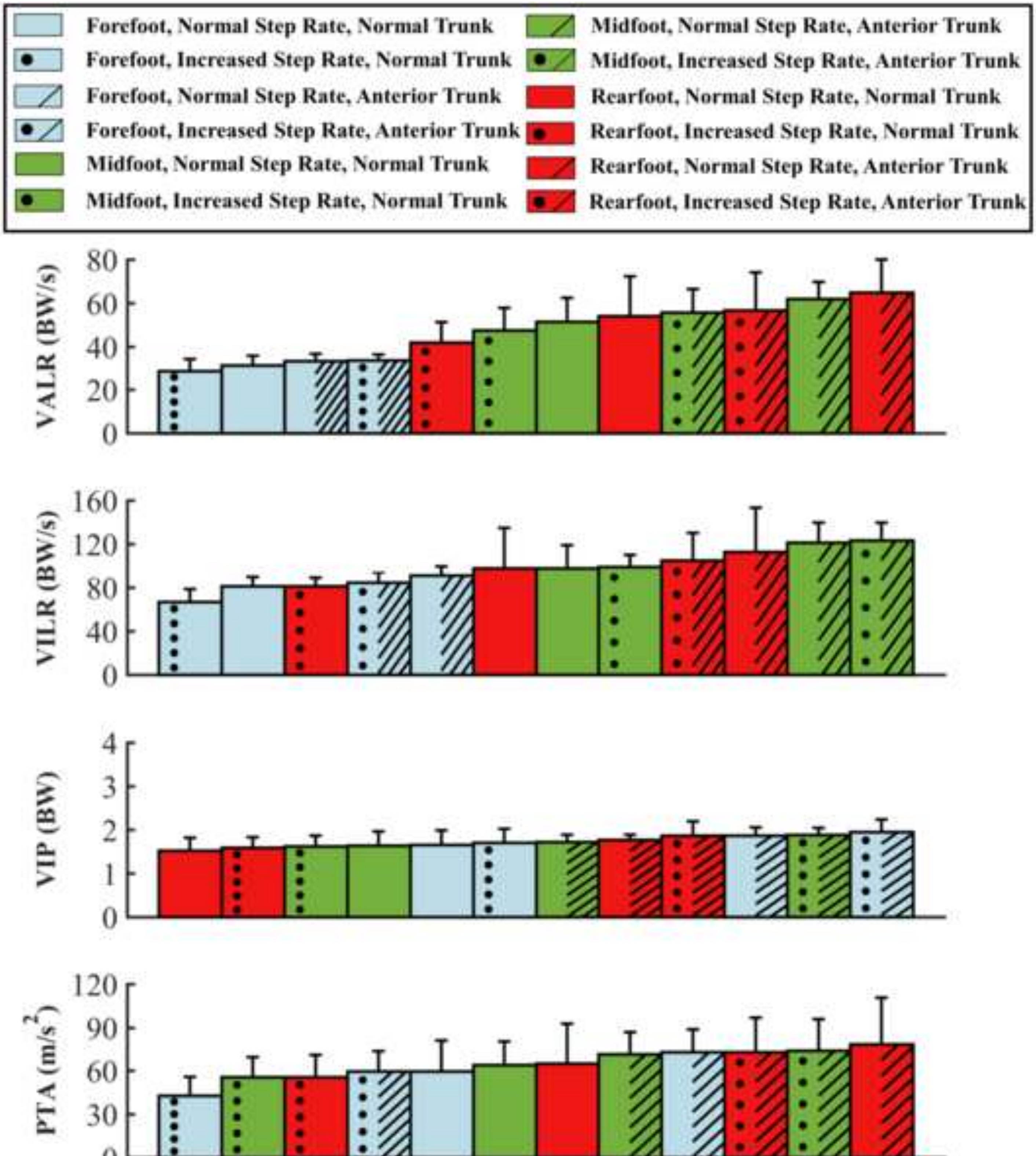
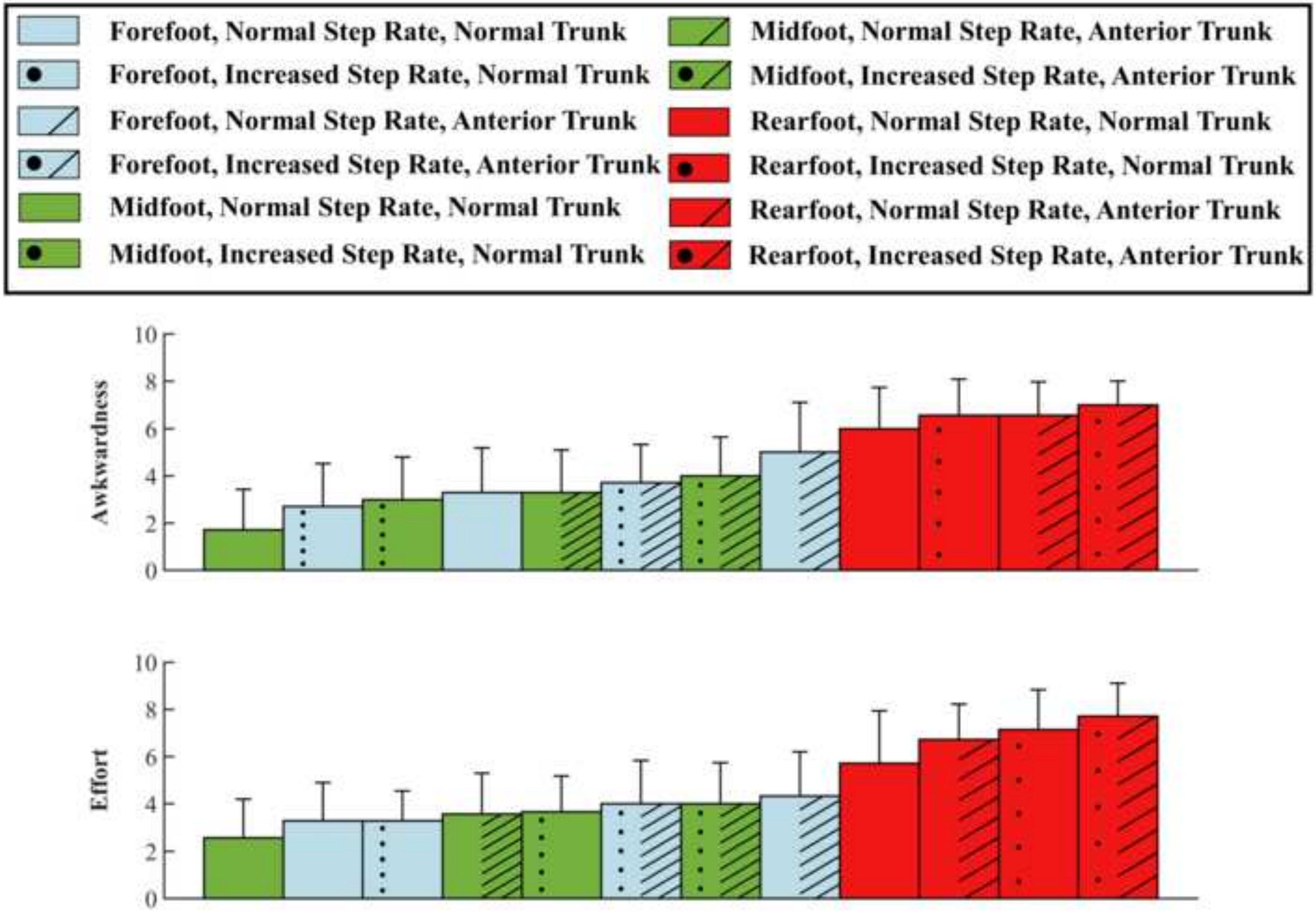

Forefoot, Normal Step Rate, Normal Trunk
Forefoot, Increased Step Rate, Normal Trunk
Forefoot, Normal Step Rate, Anterior Trunk
Forefoot, Increased Step Rate, Anterior Trunk
Midfoot, Normal Step Rate, Normal Trunk
Midfoot, Increased Step Rate, Normal Trunk
Midfoot, Normal Step Rate, Anterior Trunk
Midfoot, Increased Step Rate, Anterior Trunk
Rearfoot, Normal Step Rate, Normal Trunk
Rearfoot, Increased Step Rate, Normal Trunk
Rearfoot, Normal Step Rate, Anterior Trunk
Rearfoot, Increased Step Rate, Anterior Trunk
VALR (BW/s)
0
20
40
60
80
VILR (BW/s)
0
40
80
120
160
VIP (BW)
0
1
2
3
4
PTA (m/s²)
0
30
60
90
120

Figure 4


Forefoot, Normal Step Rate, Normal Trunk
Forefoot, Increased Step Rate, Normal Trunk
Forefoot, Normal Step Rate, Anterior Trunk
Forefoot, Increased Step Rate, Anterior Trunk
Midfoot, Normal Step Rate, Normal Trunk
Midfoot, Increased Step Rate, Normal Trunk
Midfoot, Normal Step Rate, Anterior Trunk
Midfoot, Increased Step Rate, Anterior Trunk
Rearfoot, Normal Step Rate, Normal Trunk
Rearfoot, Increased Step Rate, Normal Trunk
Rearfoot, Normal Step Rate, Anterior Trunk
Rearfoot, Increased Step Rate, Anterior Trunk
Awkwardness
Effort
0
2
4
6
8
10

	Running Condition			Statistical Significance		
	Forefoot	Midfoot	Rearfoot	p-val Forefoot-Midfoot	p-val Forefoot-Rearfoot	p-val Midfoot-Rearfoot
VALR (BW/s)	31.27±4.41	51.38±10.94	53.98±18.26	**< 0.05**	**< 0.05**	0.98
VILR (BW/s)	81.33±8.50	98.14±20.84	97.67±37.09	**< 0.05**	**< 0.05**	0.66
VIP(BW)	1.65±0.33	1.64±0.32	1.52±0.29	0.99	0.78	0.47
PTA (m/s^2)	59.84±20.98	64.33±15.85	65.23±27.18	0.84	0.18	0.60
Awkwardness	3.29±1.89	1.71±1.70	6.00±1.73	**< 0.05**	**< 0.05**	**< 0.05**
Effort	3.29±1.60	2.57±1.62	5.72±2.21	**< 0.05**	**< 0.05**	**< 0.05**

	Running Condition		
	Normal Step Rate	Increased Step Rate	p-val
VALR (BW/s)	51.38±10.94	47.31±10.39	**< 0.05**
VILR (BW/s)	98.14±20.84	99.40±10.65	0.97
VIP(BW)	1.64±0.32	1.62±0.24	0.34
PTA (m/s^2)	64.33±15.85	55.80±13.60	0.07
Awkwardness	1.71±1.70	3.00±1.79	**< 0.05**
Effort	2.57±1.62	3.67±1.51	**< 0.05**

	Running Condition		
	Normal Trunk Lean	Anterior Trunk Lean	p-val
VALR (BW/s)	51.38±10.94	62.00±7.66	< **0.05**
VILR (BW/s)	98.14±20.84	121.23±18.42	< **0.05**
VIP(BW)	1.64±0.32	1.72±0.16	0.76
PTA (m/s^2)	64.33±15.85	71.50±15.10	0.13
Awkwardness	1.71±1.70	3.29±1.80	< **0.05**
Effort	2.57±1.62	3.57±1.72	< **0.05**

P value	**FFS+ NSR+ NTL**	**FFS +HSR+ NTL**	**FFS+ NSR+ ATL**	**FFS+ HSR+ ATL**	**MFS+ NSR+ NTL**	**MFS+ HSR+ NTL**	**MFS+ NSR+ ATL**	**MFS+ HSR+ ATL**	**RFS+ NSR+ NTL**	**RFS+ HSR+ NTL**	**RFS+ NSR+ ATL**	**RFS+ HSR+ ATL**
FFS+NSR+NTL		< **0.05**	0.90	0.86	< **0.05**	0.15	< **0.05**	< **0.05**	< **0.05**	0.39	< **0.05**	< **0.05**
FFS+HSR+NTL	< **0.05**		< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+NSR+ATL	0.90	< **0.05**		0.63	< **0.05**	0.25	< **0.05**	< **0.05**	< **0.05**	0.59	< **0.05**	< **0.05**
FFS+HSR+ATL	0.86	< **0.05**	0.63		< **0.05**	0.23	< **0.05**	< **0.05**	< **0.05**	0.55	< **0.05**	< **0.05**
MFS+NSR+NTL	< **0.05**	< **0.05**	< **0.05**	< **0.05**		< **0.05**	< **0.05**	0.88	0.98	0.95	< **0.05**	< **0.05**
MFS+HSR+NTL	0.15	< **0.05**	0.25	0.23	< **0.05**		< **0.05**	< **0.05**	< **0.05**	0.67	< **0.05**	< **0.05**
MFS+NSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**		< **0.05**	< **0.05**	< **0.05**	0.88	0.37
MFS+HSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.88	< **0.05**	< **0.05**		0.47	< **0.05**	< **0.05**	< **0.05**
RFS+NSR+NTL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.98	< **0.05**	< **0.05**	0.47		< **0.05**	< **0.05**	0.89
RFS+HSR+NTL	0.39	< **0.05**	0.59	0.55	0.95	0.67	< **0.05**	< **0.05**	< **0.05**		< **0.05**	< **0.05**
RFS+NSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.88	< **0.05**	< **0.05**	< **0.05**		0.36
RFS+HSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.37	< **0.05**	0.89	< **0.05**	0.36	

P value	FFS+NSR+NTL	FFS+HSR+NTL	FFS+NSR+ATL	FFS+HSR+ATL	MFS+NSR+NTL	MFS+HSR+NTL	MFS+NSR+ATL	MFS+HSR+ATL	RFS+NSR+NTL	RFS+HSR+NTL	RFS+NSR+ATL	RFS+HSR+ATL
FFS+NSR+NTL		< **0.05**	0.33	0.72	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.84	< **0.05**	< **0.05**
FFS+HSR+NTL	< **0.05**		< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+NSR+ATL	0.33	< **0.05**		0.93	0.97	0.92	< **0.05**	< **0.05**	0.55	0.94	< **0.05**	< **0.05**
FFS+HSR+ATL	0.72	< **0.05**	0.93		0.70	< **0.05**	< **0.05**	< **0.05**	0.89	0.72	< **0.05**	< **0.05**
MFS+NSR+NTL	< **0.05**	< **0.05**	0.97	0.70		0.97	< **0.05**	< **0.05**	0.66	0.50	< **0.05**	0.70
MFS+HSR+NTL	< **0.05**	< **0.05**	0.92	< **0.05**	0.97		< **0.05**	< **0.05**	0.15	< **0.05**	< **0.05**	0.19
MFS+NSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**		0.58	< **0.05**	< **0.05**	0.19	0.94
MFS+HSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.58		< **0.05**	< **0.05**	0.96	0.78
RFS+NSR+NTL	< **0.05**	< **0.05**	0.55	0.89	0.66	0.15	< **0.05**	< **0.05**		< **0.05**	< **0.05**	< **0.05**
RFS+HSR+NTL	0.84	< **0.05**	0.94	0.72	0.50	< **0.05**	< **0.05**	< **0.05**	< **0.05**		< **0.05**	< **0.05**
RFS+NSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.19	0.96	< **0.05**	< **0.05**		0.82
RFS+HSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.70	0.19	0.94	0.78	< **0.05**	< **0.05**	0.82	

P value	FFS+ NSR+ NTL	FFS +HSR+ NTL	FFS+ NSR+ ATL	FFS+ HSR+ ATL	MFS+ NSR+ NTL	MFS+ HSR+ NTL	MFS+ NSR+ ATL	MFS+ HSR+ ATL	RFS+ NSR+ NTL	RFS+ HSR+ NTL	RFS+ NSR+ ATL	RFS+ HSR+ ATL
FFS+NSR+NTL		0.59	0.76	0.85	0.99	0.56	0.63	0.80	0.78	0.41	0.44	0.64
FFS+HSR+NTL	0.59		0.73	0.81	0.52	0.49	0.59	0.76	0.38	0.41	0.61	0.67
FFS+NSR+ATL	0.76	0.73		0.64	0.35	0.32	0.42	0.59	0.21	0.24	0.43	0.50
FFS+HSR+ATL	0.85	0.81	0.64		0.26	0.23	0.33	0.50	0.10	0.15	0.35	0.41
MFS+NSR+NTL	0.99	0.52	0.35	0.26		0.34	0.76	0.80	0.47	0.45	0.64	0.71
MFS+HSR+NTL	0.56	0.49	0.32	0.23	0.34		0.66	0.83	0.44	0.47	0.67	0.73
MFS+NSR+ATL	0.63	0.59	0.42	0.33	0.76	0.66		0.73	0.34	0.37	0.57	0.63
MFS+HSR+ATL	0.80	0.76	0.59	0.50	0.80	0.83	0.73		0.07	0.20	0.40	0.47
RFS+NSR+NTL	0.78	0.38	0.21	0.10	0.47	0.44	0.34	0.07		0.59	0.78	0.85
RFS+HSR+NTL	0.41	0.41	0.24	0.15	0.45	0.47	0.37	0.20	0.59		0.75	0.82
RFS+NSR+ATL	0.44	0.61	0.43	0.35	0.64	0.67	0.57	0.40	0.78	0.75		0.62
RFS+HSR+ATL	0.64	0.67	0.50	0.41	0.71	0.73	0.63	0.47	0.85	0.82	0.62	

P value	**FFS+ NSR+ NTL**	**FFS +HSR+ NTL**	**FFS+ NSR+ ATL**	**FFS+ HSR+ ATL**	**MFS+ NSR+ NTL**	**MFS+ HSR+ NTL**	**MFS+ NSR+ ATL**	**MFS+ HSR+ ATL**	**RFS+ NSR+ NTL**	**RFS+ HSR+ NTL**	**RFS+ NSR+ ATL**	**RFS+ HSR+ ATL**
FFS+NSR+NTL		< **0.05**	< **0.05**	0.52	0.84	0.62	< **0.05**	< **0.05**	0.18	0.27	< **0.05**	< **0.05**
FFS+HSR+NTL	< **0.05**		< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+NSR+ATL	< **0.05**	< **0.05**		< **0.05**	< **0.05**	< **0.05**	0.12	0.84	< **0.05**	< **0.05**	0.60	0.18
FFS+HSR+ATL	0.52	< **0.05**	< **0.05**		0.93	0.49	< **0.05**	< **0.05**	0.97	0.91	< **0.05**	< **0.05**
MFS+NSR+NTL	0.84	< **0.05**	< **0.05**	0.93		0.07	0.13	< **0.05**	0.60	0.27	< **0.05**	< **0.05**
MFS+HSR+NTL	0.62	< **0.05**	< **0.05**	0.49	0.07		< **0.05**	< **0.05**	0.98	0.53	< **0.05**	< **0.05**
MFS+NSR+ATL	< **0.05**	< **0.05**	0.12	< **0.05**	0.13	< **0.05**		0.49	0.47	< **0.05**	0.36	0.76
MFS+HSR+ATL	< **0.05**	< **0.05**	0.84	< **0.05**	< **0.05**	< **0.05**	0.49		< **0.05**	< **0.05**	0.49	0.98
RFS+NSR+NTL	0.18	< **0.05**	< **0.05**	0.97	0.60	0.98	0.47	< **0.05**		0.52	< **0.05**	< **0.05**
RFS+HSR+NTL	0.27	< **0.05**	< **0.05**	0.91	0.27	0.53	< **0.05**	< **0.05**	0.52		< **0.05**	< **0.05**
RFS+NSR+ATL	< **0.05**	< **0.05**	0.60	< **0.05**	< **0.05**	< **0.05**	0.36	0.49	< **0.05**	< **0.05**		0.91
RFS+HSR+ATL	< **0.05**	< **0.05**	0.18	< **0.05**	< **0.05**	< **0.05**	0.76	0.98	< **0.05**	< **0.05**	0.91	

ACCEPTED MANUSCRIPT

P value	FFS+ NSR+ NTL	FFS +HSR+ NTL	FFS+ NSR+ ATL	FFS+ HSR+ ATL	MFS+ NSR+ NTL	MFS+ HSR+ NTL	MFS+ NSR+ ATL	MFS+ HSR+ ATL	RFS+ NSR+ NTL	RFS+ HSR+ NTL	RFS+ NSR+ ATL	RFS+ HSR+ ATL
FFS+NSR+NTL		< **0.05**	< **0.05**	0.95	< **0.05**	0.22	0.16	0.15	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+HSR+NTL	< **0.05**		< **0.05**	< **0.05**	< **0.05**	0.44	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+NSR+ATL	< **0.05**	< **0.05**		< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.92	< **0.05**	< **0.05**	< **0.05**
FFS+HSR+ATL	0.95	< **0.05**	< **0.05**		< **0.05**	0.96	0.99	0.12	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+NSR+NTL	< **0.05**	< **0.05**	< **0.05**	< **0.05**		< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+HSR+NTL	0.22	0.44	< **0.05**	0.96	< **0.05**		0.37	0.93	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+NSR+ATL	0.16	< **0.05**	< **0.05**	0.99	< **0.05**	0.37		0.97	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+HSR+ATL	0.15	< **0.05**	< **0.05**	0.12	< **0.05**	0.93	0.97		< **0.05**	< **0.05**	< **0.05**	< **0.05**
RFS+NSR+NTL	< **0.05**	< **0.05**	0.92	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**		0.16	0.99	0.65
RFS+HSR+NTL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.16		0.97	0.06
RFS+NSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.99	0.97		0.13
RFS+HSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.65	0.06	0.13	

P value	FFS+ NSR+ NTL	FFS +HSR+ NTL	FFS+ NSR+ ATL	FFS+ HSR+ ATL	MFS+ NSR+ NTL	MFS+ HSR+ NTL	MFS+ NSR+ ATL	MFS+ HSR+ ATL	RFS+ NSR+ NTL	RFS+ HSR+ NTL	RFS+ NSR+ ATL	RFS+ HSR+ ATL
FFS+NSR+NTL		0.54	0.78	0.85	< **0.05**	0.23	0.10	0.67	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+HSR+NTL	0.54		< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.40	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+NSR+ATL	0.78	< **0.05**		0.97	< **0.05**	0.28	0.98	0.97	< **0.05**	< **0.05**	< **0.05**	< **0.05**
FFS+HSR+ATL	0.85	< **0.05**	0.97		< **0.05**	0.30	0.31	0.97	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+NSR+NTL	< **0.05**	< **0.05**	< **0.05**	< **0.05**		< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+HSR+NTL	0.23	< **0.05**	0.28	0.30	< **0.05**		0.62	0.81	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+NSR+ATL	0.10	0.40	0.98	0.31	< **0.05**	0.62		0.77	< **0.05**	< **0.05**	< **0.05**	< **0.05**
MFS+HSR+ATL	0.67	< **0.05**	0.97	0.97	< **0.05**	0.81	0.77		< **0.05**	< **0.05**	< **0.05**	< **0.05**
RFS+NSR+NTL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**		0.87	0.38	< **0.05**
RFS+HSR+NTL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.87		0.54	0.32
RFS+NSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.38	0.54		0.13
RFS+HSR+ATL	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	< **0.05**	0.32	0.13	

	Statistical Significance			
	p-val FSP&SR	p-val FSP&TL	p-val SR&TL	p-val FSP&SR&TL
VALR (BW/s)	0.46	0.09	0.40	0.66
VILR (BW/s)	0.59	0.07	0.30	0.88
VIP(BW)	0.97	0.77	0.40	0.71
PTA (m/s^2)	0.26	0.67	0.27	0.87
Awkwardness	< **0.05**	0.36	0.80	0.05
Effort	< **0.05**	0.39	0.24	< **0.05**