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Orthotic insoles show effects on knee kinematics during pedaling in recreational cyclists

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Abstract

Orthotic insoles in cycling shoes are an intervention used to correct pedaling mechanics in riders, which has received little attention in the literature. This study was designed to test the hypothesis that the use of orthotic insoles in cycling shoes would alter pedaling mechanics of uninjured recreational cyclists. Additionally, it was hypothesized that the insole that allowed the lowest level of lateral knee displacement would be related to the rider's arch height. Nine cyclists were evaluated during four cycle ergometer maximal power output tests, using four different insole configurations (flat [no insole], low, medium, and high arch support) in a random order. Video recordings were used to measure lateral knee displacement. Incremental exercise tests were performed at least 48 hours apart to control for fatigue. The non-flat insole that resulted in the lowest level of lateral knee displacement was identified for each leg. There was no relationship between arch variable and the "best fit" insole. Because the best fit insole was not the same between feet for most cyclists, the statistical model was run twice, with the best insole for the dominant leg and non-dominant leg identified as the overall "best fit" insoles. When the best fit for the dominant leg was identified as the overall "best fit" insole, it produced effects on dominant knee lateral displacement (p=.001). The implication of these findings is that orthotic insoles have minimal effects on pedaling mechanics.

Keywords: cycling, knee, kinematics, biomechanics, pedaling

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Introduction

Riders are fit to their bicycles at three points: the hands, the saddle, and the foot-shoe-cleat-pedal (FSCP) interface. There are three basic techniques that are used to effectively achieve this fit: experienced-based direct observation, technology-assisted indirect observation, and anthropometrically-based formula fitting (Hogg, 2012). No fitting method takes full advantage of existing research concerning changes in aspects of the FSCP interface and their potential effects on the mechanics of associated movements of the legs (Asplund & St. Pierre, 2005; Christiaans & Bremner, 1997; Alderson, 2015). Researchers have examined the individual components of the FSCP interface, not considering how altering a single aspect can affect the mechanics of the whole, and of a rider's entire lower extremity kinetics, kinematics, and performance (Harper, 2014; van Sickle & Hull, 2007; Gregor & Wheeler, 1994). Additionally, problems with the FSCP interface have the potential to cause discomfort or injury throughout the cyclist's body (Asplund & St. Pierre, 2005).

Foot inversion or eversion has been shown to alter knee moments during cycling (Ruby, Hull, Kirby, & Jenkins, 1992; Gregor & Wheeler, 1994; Johnston, 2007; Sanner & O'Halloran, 2000). Traditionally, the shoe-cleat interface has been examined for two purposes: equalizing leg length discrepancies and determining optimal fore-aft cleat placement (Asplund & St. Pierre, 2005; Callaghan, 2005). Spacers have been used to correct leg length discrepancies, while changes in gastrocnemius activation has been examined by adjusting fore-aft cleat placement on the shoe (Ruby et al, 1992; Johnston, 2007; Sanner & O'Halloran, 2000; Van Sickle & Hull, 2007). In addition to the work of van Sickle and Hull (2007), Ramos Ortega, et al (2012), established that placing the base of the cleat at 43% from tip of the shoe placed the pedal spindle at the head of the first metatarsal. This is a commonly suggested placement, but as the authors state, there are no scientific criteria establishing how to ensure cleat position is putting the foot in the correct position over the pedal spindle. The cleat-pedal connection is not as well investigated as the foot-shoe or shoe-cleat components.

Research has also shown that increasing the freedom of transverse rotation of the foot relative to the pedal (float) will alter knee joint moments (Ruby & Hull, 1993). Easing the constraints on where and how forces can be applied at the foot has the potential to mitigate the risk of injury further up the leg (Asplund & St. Pierre, 2005; Callaghan, 2005; Ruby & Hull, 1993; Sanner & O'Halloran, 2000). Recently manufacturers have begun selling shoes packaged with modular insoles to compensate for each rider's unique foot structure. Because of foot and ankle anatomy, changing any component within the FSCP interface should affect the mechanics of more proximal structures. These mechanics determine how wedges, spacers, or insoles can be used to facilitate the effective transfer of force from the legs to the pedals (Dinsdale & Williams, 2010; Sinclair et al, 2014; Yang, 2013).

Although classified as a hinge joint, the structure of the tibiotalar joint allows an element of rotation about the subtalar axis. Orthotic insoles are designed to control foot inversion or eversion, thereby reducing rotation of the tibia; this effect has been shown in static position or walking gait (Andreasen et al, 2012; Rodrigues et al, 2013), but not widely in cycling (below). Bringing the foot to a neutral position may help align the leg, increasing comfort, performance, and safety (Yang, 2013). There is considerable research establishing the use of insoles to support or correct motion in the tibiotalar joint of runners (McMillan & Payne, 2008; Eng & Pierrynowski, 1994), but research examining their effectiveness in producing similar corrections in cyclists during pedaling has only recently begun, and a consistent effect of insoles on pedaling kinematics is not supported by current knowledge (Sinclair et al, 2014; Yeo & Bonanno, 2014). As of this manuscript, the authors found only one study specifically examining arch support orthoses in cyclists. Of the measured variables (ankle frontal plane inversion/eversion, knee joint ROM, VL EMG, muscle power) , only ankle position and muscle power demonstrated significant changes due to insole condition (Yang, 2013). Yang's initial findings, and the lack of a consistent trend of insole effects in cyclists, support this study examining the hypothesis that insole use can affect foot position, and potentially, kinematics in cyclists.

The purpose of the current study was to examine the impact that four levels of insole support could have on kinematics in moderately active male cyclists. All cyclists were tested under all insole conditions, so it was possible to identify which insole provides the "best fit"; operationally defined as the insole that causes the least amount of lateral knee displacement while pedaling. Additionally, the strength of the relationships between individuals' arch heights and their best-fit insoles were evaluated. Because the impact of insoles during cycling is not known, this study tested the hypothesis that there would be at least one insole for each subject that would minimize lateral knee displacement while pedaling during an increasing-resistance ramp test performed on a cycle ergometer adjusted to simulate the cyclist's road bicycle.

Materials and methods

Participants

This study was designed to adhere to the research standards described by Harriss and Atkinson (2011) and was approved by the Medical Science Institutional Review Board of the Human Subjects Research Office at the University of Miami. All cyclists read and signed a written informed consent approved by the review board. Cyclists were recruited from local cycling groups. Potential cyclists were required to have more than one year of cycling-specific training, to have used their current pedals for the past three months, to not currently use arch support insoles, and to meet the requirements of the PAR-Q and American Council on Exercise (ACE) health history questionnaires. Cyclists were classified post-hoc as professional (VO_{2max} >70 ml/kg/min; 0 participants), elite (VO_{2max} 60-70 ml/kg/min; 4 participants), club (VO_{2max} 50-60 ml/kg/min; 3 participants), recreational (VO_{2max} 45-50 ml/kg/min; 0 participants), or non-cyclist (VO_{2max} <45 ml/kg/min; 2 participants) according to Ansley and Cangley (2009).

Twenty cyclists were screened and enrolled in this study. Nine cyclists (32 ± 6.3 years old, 178.6 ± 6.1cm, 83.6 ± 11.9kg) completed all 4 tests and were included in the analysis. To prevent bias, leg dominance was ascertained post-testing but pre-analysis by asking which foot each subject would put forward when performing a standing start (track stand) on a bicycle. Three cyclists identified their left leg as their dominant leg.

Experimental Procedures

After providing written consent, each subject's foot measurements were taken with the JAK-Tool Arch Height Index Measurement System (AHIMS; JAK Tool and Model, Cranbury, NJ) (Butler et al, 2008). The AHIMS was used to measure subject foot length, heel-1st metatarsal length, and arch height while sitting. This was their "unloaded" arch height. Foot length, heel-first metatarsal and arch heights were also taken while each subject was standing. To control the amount of load they were placing on their longitudinal arches, cyclists were asked to put most of their weight on the foot being measured; the contralateral foot could remain on the ground for balance purposes only. The difference between sitting (unloaded) and standing (loaded) arch height was called "arch compliance", or informally, "collapse". All measurements were made by the same certified athletic trainer. Cyclists were also required to bring their normal road bicycle to their screening visit, and the laboratory cycle ergometer (Velotron Pro, Racermate, Seattle, WA) was configured as closely as possible to the cyclist's road bike by the following parameters: (1) bottom bracket-to-saddle height, (2) front of saddle-to-handlebars distance, (3) handlebars-to-bottom bracket distance, (4) bottom bracket-saddle setback, and (5) crank length. These values were recorded and used during all subsequent trials, and cyclists were asked to not alter any dimensions of their normal road bicycle nor adjust shoe cleat position for the duration of their participation in the study. Following these procedures, cyclists were given an opportunity to familiarize themselves with the cycle ergometer, and video devices, and appointments were made for all testing sessions.

For every laboratory visit, cyclists were instructed to arrive well rested (eight hours of sleep), well hydrated (500ml of water within an hour of experimental trial), not having consumed caffeine, and fasted over the preceding eight hour period. They were required to bring their normal cycling shoes and pedals. Their pedals were affixed to the cycle ergometer.

Cycle Protocol

Cyclists preceded all tests with a 5-minute warm-up on the cycle ergometer at a self-selected, comfortable resistance. Following the warm-up, the subject began the test at 100 W, and the cycle ergometer was programmed to increase resistance by 50 W every two minutes, with the goal of reaching the end of the test (subject's VO_{2max}) in approximately 10 minutes (Buchfuhrer et al, 1983). The cycle protocol was identical for every subject for each insole condition. Cyclists were allowed to self-select a cadence, provided it was above 80 rpm. If cyclists did not voluntarily terminate a test, the research team terminated the test based on two of the four following criteria: 1) a plateau in VO_2 despite an increase in workload; 2) a heart rate within 10-15 bpm of age-predicted maximum; 3) an RER greater than 1.10; or, 4) a decrease in cadence below 80 rpm.

Kinematic Analysis

Before commencing the test, retroreflective markers were placed on each rider's left and right tibial tuberosities. These were held in place with Leukotape (Beiersdorf AG, Hamburg, DE), and further secured with black PowerFlex tape (Andover Healthcare, Salibury, MA) to create a high-contrast background. A picture of the subject prepared for an exercise trial is presented in Figure 1. A Canon FS300 camera (30FPS@480p) was placed ahead of each cyclist to record these markers in the frontal plane while they rode each trial, and 10-second clips from the end of each two minute resistance stage were selected from the whole video. Within these 10-second clips, the middle five pedal cycles beginning with the right leg at the lowest point of the pedal stroke were identified, and the lateral motion of the right and left tibial tuberosity markers were tracked for these five pedal cycles. Raw data were analyzed in the Kinovea software suite to quantify hip abduction/adduction as estimated by the movement of markers on the knee (maximum lateral position and minimum internal position). The software was calibrated to a known dimension on the bicycle frame and the mediolateral range of tibial tuberosity motion relative to bicycle ergometer frame centerline was measured by tracking the markers placed at the tibial tuberosities. The same investigator manually tracked and measured all marker displacement using the software. Values were averaged within legs per trial to provide a singular measure representative of lateral knee displacement for each leg per insole.

Test Conditions

Four insole conditions were evaluated: baseline, low, medium/neutral, and high support (Figure 2). The low, medium, and high arch support levels were created using a widely-sold two-layer cycling shoe-specific insole with a built-in "low" level of arch support (1:1 Insole system, Pearl Izumi, Louisville, CO). "High" and "medium" support levels were attained by use of high-density foam inserts that fit between the two layers at the appropriate position. The baseline insole was each subject's current insole. Cyclists passed a "no current arch support" inclusion criteria, essentially making the baseline insole the 'flat' arch support condition. Every cyclist performed their baseline test first, and then was randomized to an insole testing order using the low, medium, and high conditions. "Best Fit" insoles were defined as those non-baseline insoles which caused the least amount of lateral knee displacement for the dominant and non-dominant legs. All cyclists used their own shoes and pedals. Pedal type was noted for the purpose of analysis. Every cyclist used clipless pedals, but these are different by design i.e. some systems use spring force to return the cleat (and shoe) back into a centered position relative to the pedal ("centering float" pedals). The other system uses a "c-clip" and allows the cyclist's foot to rest anywhere within the preset range without pulling the foot back to center; these are "non-centering float" pedals. The limit screws for the c-clips were completely opened for each trial to allow maximum freedom of movement of the cyclist's feet.

Statistical Design & Analysis

Results were analyzed using SPSS Statistics for Windows, Version 20.0 (IBM Corp., Armonk, NY). Descriptive statistics are reported as Means ± SE, and frequencies are provided for categorical data. A 5 x 2 general linear mixed model (GLMM) was used to test if there was a significant difference among insole conditions (baseline, low, medium, high, and "best fit") and normally used pedals (centering or non-centering float). GLMM was chosen for two primary reasons; firstly, due to the definition of "best fit" the model calculates estimates while accounting for missing data, which the classic ANOVA cannot. Secondly, the GLMM procedure allows the direct specification of the residual covariance matrix, which negates need to satisfy the restricting assumptions of homogeneity of covariance matrices and sphericity. Covariance structures were chosen based on the method that resulted in minimization of Akaike and Bayesian Information Criterions. One of two covariance structures, either Compound Symmetry or First-Order Autoregressive, was chosen for all GLMMs. The GLMMs require that the residuals for each group by insole within the model are normally distributed (McCulloch, 2006). This was assessed using the Shapiro-Wilk test. Data were screened to remove extreme or unrealistic readings using Tukey's outlier labeling rule (Hoaglin & Iglewicz, 1987) with k = 2.1. The secondary research question, examining the relationship between arch height and "best fit" insole, was examined using a Spearman Rank-Order Correlation. Spearman's rho was chosen because arch support level was an ordinate variable based on manufacturer design of the insoles used. Additionally, because we expected arch heights to be similar by "best fit" group, rho was a more appropriate method of identifying a monotonic relationship. The assumptions of linearity, monotonicity, and no outliers were examined using a scatterplot. Alpha was set at .05 for all tests, excluding Shapiro-Wilk, which used .01 due to its sensitivity in small samples.

Results

Average left and right lateral knee displacements were computed for each insole condition. "Best Fit", previously defined as the non-baseline insole that showed the least lateral knee displacement, varied between legs in six of nine cases. Because left and right best fit insoles were not consistent across cyclists, analyses were run twice using functional "dominant" and "non-dominant" legs.

Best fit insole had no relationship to standing (loaded) arch height for either the dominant or non-dominant legs, r_s=.055 (p=.89) and r_s=.114 (p=.77), respectively. Additionally, there was no relationship between sitting (unloaded) arch height and best fit insole on the dominant (r_s=-.054, p=.89) or non-dominant (r_s=-.057, p=.885) side. Lastly, the difference between sitting and standing arch heights (arch compliance) was not related to best fit insole for the dominant, r_s=-.103, p=.791 or non-dominant legs, r_s=-.601, p=.087.

Knee Displacement

GLMMs were run to examine knee displacement for the dominant leg and non-dominant legs. For dominant leg, the differences in lateral knee displacement across insole conditions between pedal float types was not significant, $F(4,19)=.591$, p=.673. There were no differences in pedal float types, $F(1,8)=.022$, p=.886. Insoles had a significant effect on lateral knee displacement, $F(4,19)=7.837$, p=.001 (Figure 3). Pairwise comparisons revealed that best fit (M=5.228cm, SE=.343cm) insoles caused significantly less lateral knee displacement than high (M=6.038cm, SE=.363cm) and medium (M=6.535cm, SE=.387cm) levels of arch support, p=.015 and p=.001, respectively.

For non-dominant leg, the pattern of differences across insole conditions between pedal float types was not significant, $F(4,17)=.321$, p=.86. There were no differences due to pedal float types, $F(1,7)=1.714$, p=.232. Insoles had no effect on lateral knee displacement, $F(4,17)=1.826$, p=.169 (Figure 4).

Discussion

The effects orthotic insoles have on skeletal alignment are still debatable (Nigg et al, 1999; (Gross & Foxworth, 2013). Orthotic support in running shoes is an area of active research (McMillan & Payne, 2008); however, arch support in cycling shoes has little support in the literature, though bicycle fitters continue to have them available as a corrective

Figure 1. Subject prepared for exercise trial, highlighting locations of the tibial tuberosity markers.

Figure 2. Pearl Izumi 1:1 insoles used in this study. The wedges (right) represent medium (black) and high (gray) insole conditions. Image from www.trisports.com

intervention. We cannot support the use of orthotic insoles in cycling shoes as an intervention to stabilize hip abduction/adduction (lateral knee displacement) while cycling. While the identified "best fit" insole did produce significantly lower lateral knee displacement than the other experimental insole conditions, it was not significantly lower than the baseline insoles the cyclists already used. Although the "best fit" insole was not mechanically better than baseline, it was also no worse. It may be that using the rider-identified more comfortable of the two may result in safer and/or more laterally stable pedaling motion (Callaghan, 2005).

Our results indicate that arch support may affect lateral knee displacement, suggesting its usefulness to clinicians and bicycle fitters as a tool to adjust overall bicycle fit. However, a consistent effect was not shown by this study. As we hypothesized, there did exist a "best fit" insole that resulted in a lower level of lateral knee displacement compared to the other non-flat insole conditions. Contrary to what was hypothesized, "best fit" was not significantly better than the flat baseline, was not related to an individual's arch height, and in two-thirds of cyclists, differed by side. Our results indicate that despite having similar arch height and compliance levels for dominant and non-dominant legs, different levels of arch support demonstrate the "best" mechanical results for each leg. These findings indicate that when fitting a rider with orthotic insoles, care should be taken not to generalize one level of arch support as "best" or most effective application for both legs. It has been suggested that while arch support is important in running, the plantar pressure differences between running and cycling may point towards forefoot varus or valgus as the anatomic characteristic of interest when identifying "best fit" foot support (Sanderson, 1987). Recent research has concentrated on other interventions, but found minimal or no effects, in agreement with the present study (Sinclair et al, 2014; Dinsdale, 2010; Yeo & Bonanno, 2014).

Ideally, insole or orthotic characteristics would match subject characteristics. Nigg, Nurse, and Stefanyshyn (1999) assert that improved alignment or performance could be used as possible diagnostic markers of a subject's "optimal" insole. The study performed no analyses to confirm this assertion, and the authors ultimately proposed that comfort may be the key variable related to fit, which could explain why "best fit" insoles were often different between legs. It should not be ignored that "baseline" insoles will have some level of comfort associated with their use, and studies examining subjective perception of insole comfort should address change when using different levels of support.

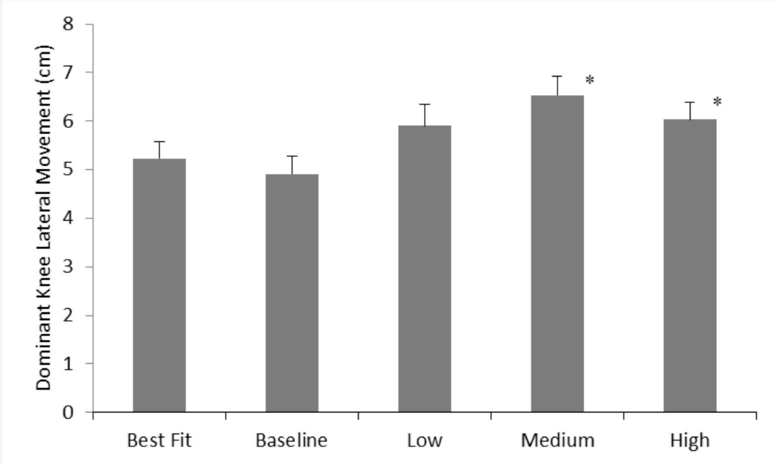

Figure 3 The effects of insole condition on lateral knee displacement in the dominant leg.

* Significantly higher than "Best Fit", p<.05.

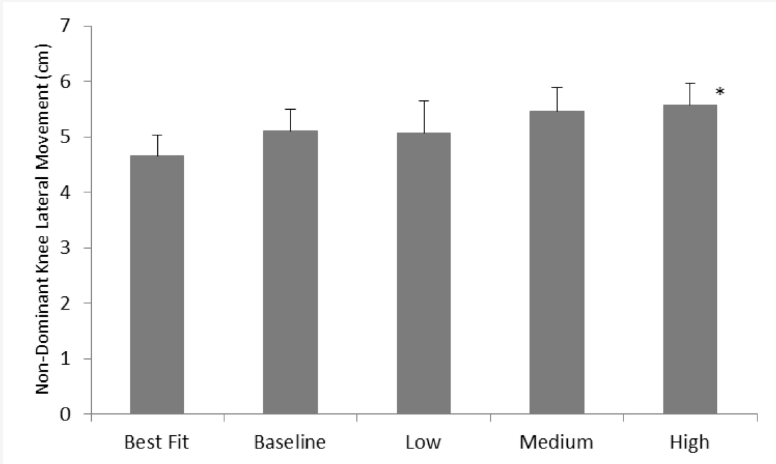

Figure 4 The effects of insole condition on lateral knee displacement in the non-dominant leg.

* Significantly higher than "Best Fit", p<.05.

In addition to comfort, imbalances in lower limb strength or leg dominance could explain the dissimilar optimal insole heights between legs. Chhibber and Singh (1970) studied 10 cadavers, and found that dominant legs had significantly more muscle and total mass. Jacobs et al (2005) showed that dominant and non-dominant muscles (specifically, hip abductors) had significant fatigability differences. These findings support our conclusion that dimensional similarities between dominant and non-dominant legs, specifically represented in the current study as differences in longitudinal arch characteristics, are not a strong enough basis by which to assign overall "best fit" insoles.

Since arch height was not related to the "best fit" insole in this study, an important goal for future research is to identify alternative predictors of individuals' "best fit" insoles. As outlined above, Nigg et al. (1999) offered some guidance to identify characteristics that would make predicting a subject's ideal insole a simpler task; however, the findings of the current study indicate that neither arch height, nor arch compliance are suitable predictors.

This study used a carefully selected sample composed of male cyclists; this limits the generalizability of this study. Excluding female riders, while removing gender as a confounding variable, also means that these results do not take into account large anatomical differences between riders of different genders (increased Q-angle; Horton & Hall, 1989: altered patellofemoral joint biomechanics; Csintalan et al, 2002). In addition to being gender-limited, the sample size (n=9) was also smaller than optimal for this study.

Also, this study recruited riders who used both centering-float and non-centering-float pedal systems. This is important to note because "non-centering" float allows the cleat (and shoe and foot) to rotate freely above the pedal body. Centering-float-style pedal systems allow rotation before the cleat disengages from the pedal, but are built in such a way that the spring tension of the pedal is constantly trying to pull the cleat (and thus, shoe) back into line with the pedal body.

Lastly, the results of this study represent acute changes due to insole use. Previous research examining changes in kinematics and kinetics with long-term insole use has concentrated on treatment of osteoarthritis in the knees, but suggests that insoles may cause chronic changes (Güner et al, 2015; Hsu et al 2015). The current study design used one trial per insole, with no acclimatization period, and thus would not have shown such changes. Though the literature concentrates on walking gait, Alsancak (2012) showed that long-term insole use significantly reduced knee varus moment. Toda and Tsukimura (2004) also demonstrated subjective improvement in gait function via visual analogue scale (VAS) and Lequesne Index scores in women with osteoarthritis. Schwellnus, Jordaan, and Noakes (1990) showed that insole use attenuated injury rates over a 9-week training period. Stöggl et al (2010) showed that 10 weeks of training with an experimental shoe resulted in gait characteristics similar to walking in control shoes. While results for gait show that insoles are effective, support of the assertion that insoles in cycling shoes may show more effects on mechanical, electromyographical, and performance variables after prolonged use and adaptation is lacking (Sinclair et al, 2014; Yeo & Bonanno, 2014). Future studies on insoles in cycling shoes should be longitudinal to allow the evaluation of any effects insoles might have after adaptation phases or prolonged use.

Conclusions

In conclusion, arch support insoles in cycling shoes may be an effective intervention for acutely altering pedaling kinematics, but their long-term effects are still not defined. Continued study of the distinct effects of alterations in the FSCP interface can eventually be synthesized to build a complete model to explain the behavior of the pedaling leg. Future research should use larger and more varied samples to further examine the effects of float type, gender differences, or forefoot correction (which can be applied at the insole or the cleat) on motion of the leg. Study designs should also explore the long term effects of training with foot position correction. Longitudinal studies, or trial designs using longer, steady-state rides or time trials, may identify power output or oxygen consumption effects that were not seen in this study. Additionally, since "best fit" insoles were often different from one side to the other, a similar study should be carried out with each leg's "best fit" insole used on that respective leg, to examine if the combination of the "best" for each leg produces greater impact than that recorded in this study.

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