Alternative shoe closure designs alter biomechanical performance during agility-based movements

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The objective of this research was to determine if three alternative shoe upper closures improve biomechanical performance measures relative to a standard lace closure in court-based movements. NCAA Division 1 and club-level male athletes recruited from lacrosse, soccer, tennis, and rugby performed four court-based movements: Lateral Skater Jump repeats (LSJ), Countermovement Jump repeats (CMJ), Triangle Drop Step drill (TDS), and Anterior-Posterior drill (AP). Each athlete performed the movements in four shoe upper closures: Standard Closure, Lace Replacement, Y Wrap, and Tri Strap. Ground contact time, peak eccentric rate of force development (RFD), peak concentric GRF, peak concentric COM power, eccentric work, concentric work, and movement completion time were measured. Tri Strap saw improvements in four of seven biomechanical variables during CMJ and LSJ and one variable during TDS. Lace Replacement delivered improvements in one performance measure during CMJ, LSJ, and AP, and two variables in TDS. Y Wrap improved performance in three performance measures during LSJ and impaired performance in two measures during CMJ and three measures during AP. Tri Strap provided the most consistent performance improvements across all movements. This study allowed for the mechanical properties of the shoe lower to remain consistent across designs to examine if an alternative shoe upper closure could enhance performance. Our results indicate that increased proprioception and/or mechanical properties due to the alternative closures, especially Tri Strap, improves athlete performance, which concludes that the design of the shoe upper is an essential consideration in shoe design.

Keywords: shoe closure; shoe design; biomechanical performance; shoe upper; athletic shoe

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1. Introduction

Selecting footwear is an important and personal choice for any athlete, and many factors are considered by the footwear designer to produce the right shoe for the athlete consumer. The goal of a shoe is to provide a platform for shock attenuation, functional stability, and support during the gait cycle propulsion phase in all three dimensions of foot movement (Dicharry and Magrum, 2012). Reinschmidt and Nigg (2000) characterise the important functional factors of a shoe to be injury prevention, comfort, and performance. Athletic footwear is generally divided into two categories—running and court (tennis, basketball, volleyball, etc.)—with cross-training footwear combining design characteristics of both running and court categories. The vast majority of research investigations in footwear design examine functional factors in running. However, a recent increase in court-related investigations, mainly on basketball shoes, indicates that interest in the design of court/field footwear is growing (Kong 2018; Brauner et al. 2012; Lam et al. 2011; Worobets and Wannop 2015; Jastifer et al. 2017). The functional factors for shoe design in court sports also inform field sports (e.g., soccer, football, lacrosse, and rugby) because footwear enables all these athletes to safely and quickly perform landing, cutting, and jumping manoeuvres. This investigation focuses on how court shoe design, particularly the design of the closure of the shoe upper, can influence the functional factor of performance.

Traditional shoe design emphasises a shoe's ability to stop, support, and stabilise the foot. Designers typically address these goals by modifying the shoe bottom package while the shoe upper is primarily responsible for containment (Dicharry and Magrum, 2012). The shoe lower includes parts of the shoe that exist below the foot, which vary across shoes in material properties, traction, arch support, and toe-to-heel rise. Motion control in the rearfoot (subtalar joint) and midfoot (arch) are primary design targets and the subject of many investigations that attempt to quantify foot motion within the shoe (Arnold and Bishop, 2013).

While the majority of shoe designs focus on the midsole, the shoe upper further facilitates the foot-to-shoe connection and provides the environment for the foot to operate. The shoe upper has the largest contact area with the foot of any other part of the shoe (Onodera et al. 2017), and likely influences proprioception in addition to comfort, fit, and mechanical properties. Designers recognise the importance of fit to an athlete, but this has traditionally been defined by how the shoe last imitates an individual athlete (McPoil, 2000). Alternative closure designs that are highly adjustable may allow a generic last to fit a variety of individuals. In turn, this may influence factors such as proprioceptive acuity and performance. To our knowledge, no research is available on alternative closures in athletic shoe design.

Although performance is an essential factor cited in functional shoe design (Reinschmidt and Nigg, 2000; Clifton et al. 2011), very few court-related investigations have focused on performance outcomes. Numerous factors, such as skill level, strength, conditioning, fatigue, psychology, and environment, affect an athlete's performance. The effects of specific equipment like shoes on performance can be challenging to assess. Most investigations involving court or field sports have focused on the ankle, rear-foot, or mid-foot motion (Lafortune 1997; Reinschmidt et al. 1992; Sandrey et al. 2001; Tik-Pui et al. 2007) without referencing the performance outcome. A notable exception to this is Hennig and Sterzing (2010), who report on several investigations that indicate how different properties of soccer shoes—comfort, traction, stability—can affect performance. These investigations examined specific tasks such as maximum ball velocity and accuracy during a kick, in addition to broader athletic performance outcomes such as goals scored and injury rates (Hannig and Sterzing, 2010).

Measuring biomechanical performance during specific court-based movements may provide a quick and efficient feedback loop and enable fast iteration on specific aspects of shoe

design, such as the closure of the shoe upper. Biomechanical performance variables are defined in this paper as quantifiable performance measures collected using biomechanical equipment such as force platforms and motion capture technology. Although there are many methods to assess biomechanical performance during direction changes and jumping (Jensen et al. 2007; McLellan et al. 2011; Van Lieshout et al. 2014), the effects of specific shoe designs on these performance variables have not been investigated.

The objective of this investigation was to determine if changes to the shoe upper—in the form of three alternative shoe closures—will affect biomechanical performance compared to standard lacing during court-based agility movements. The alternative closures, made possible by an adjustable dial, lightweight laces, and low friction lace guides, are designed to enhance the fit of the shoe upper to the athlete's foot. We hypothesised that each alternative closure design would improve measures of biomechanical performance compared to a standard lace shoe. Biomechanical performance improvements resulting from modifications only to the shoe closure would provide evidence that altering the fit of the shoe upper can affect performance.

2. Materials and Methods

High-level athletes from court- and field-based sports performed a series of four court-based movements while wearing the same shoe with four different closures. Seven measures were quantified for each repetition of the movements. Performance for each alternative closure was compared to the retail laced version of the shoe (Standard Closure) using a linear mixed model. The University of Denver Institutional Review Board approved this investigation, and all data were collected in the Human Dynamics Laboratory at the University of Denver.

2.1 Participants

Thirty-one NCAA D1 and club-level male athletes playing lacrosse, rugby, soccer, and tennis from the University of Denver and surrounding community participated in this investigation (Table 1). A modified activity screening questionnaire based on the International Physical Activity Questionnaire (IPAQ) was used to ensure that all athletes were highly active and dedicated more than 6 hours each week specifically to playing or training for their sport.

Shoe sizes were limited to the range most commonly worn in D1 and club level athletes in lacrosse, rugby, soccer, and tennis at the University of Denver, sizes 9.5 to 11.5 (Figure 1). Other court sports, such as basketball, were excluded because the range of shoe sizes needed (12-14) was not available, and to reduce variance in height and weight in the sample.

2.2 Instrumentation

Before performing the court-based movements, each athlete was outfitted with 38 reflective markers (22 single markers and four clusters of four markers), which included a full lower extremity marker set and an abbreviated HAT segment (head, arms, trunk) marker set. An eleven-camera passive motion capture system (Vicon Motion Systems) was used to capture full body segment motion at 100 Hz using Vicon Nexus Capture software (Motion Systems Ltd, Oxford, UK). Ground reaction force information was sampled at 1000Hz from four force platforms (Bertec, Columbus, OH). Marker data were filtered using a 4th order zero-phase-lag low-pass Butterworth filter (10 Hz cutoff), and ground reaction forces were filtered using a 4th order zero-phase-lag low-pass Butterworth filter (30 Hz cutoff).

2.3 Court-based Movements

Each athlete performed two repetitions of four court-based movements within a round of testing: Lateral Skater Jump repeats (LSJ), Countermovement Jump repeats (CMJ), Anterior-Posterior Drill (AP), Triangle Drop Step Drill (TDS). As a whole, these movements were chosen because court and field athletes use a series of non-unique direction changes and jumping that span across many sports, and agility and power training for performance and injury prevention mimic these movements. The LSJ and CMJ were chosen because they are typical agility training movements performed in a strength and conditioning environment. The TDS and AP movements incorporated a sport-related motion (ball pass or racquet forehand) to help the movement reflect a more sport-like situation than the agility training movements. Before and during the experimental session, each athlete reviewed the video we created titled [Athlete Instructions](#), which contained instructed demonstrations of each of the four movements.

Lateral Skater Jump Repeat (LSJ): Each athlete performed eight subsequent lateral skater jumps with their dominant foot targeting a force platform, and their non-dominant foot targeting a box set laterally to the force platform at a distance equal to shoulder height. Athletes planted their dominant foot as hard as possible and changed direction off the dominant foot as fast as possible.

Countermovement Jump Repeat (CMJ): Each athlete performed eight continuous countermovement jumps as high as possible, with arm swing above the head and legs straight while in the air, without pausing between jumps (see guidelines in Cormack et al. 2008). Countermovement depth was not controlled. CMJs were performed with feet shoulder-width apart with each foot on a separate force platform.

Triangle Drop Step Drill (TDS): Two boxes were set laterally to each other 2.8 meters apart. The coloured box was set at 2.8 meters away on a line at a 45-degree angle from force

platform 4. The white box was set at a 45-degree angle, 2.8 meters away from force platform 1. Right foot dominant athletes began in the coloured box and backpedalled to force platform 4, planting their right foot as hard as possible and changing direction as fast as possible back to the coloured box. Athletes then moved sideways in a pattern of their choice while continuing to face forward over to the white box. At the white box, the athlete performed a sport-specific motion (e.g., ball pass, swing) before backpedalling to force platform 1, where they planted their left foot as hard as possible and changed direction back to the white box as fast as possible. They performed a sport-specific movement in the white box before moving sideways back to the coloured box. This pattern was repeated three times for a total of six force platform hits (Figure 2). Left foot dominant athletes reversed the pattern, beginning in the white box and performing an athletic movement in the coloured box. Each athlete was instructed, "to perform six swings/passes" to keep their focus on the sport-specific movement rather than the force platform.

Anterior-Posterior Drill (AP): Athletes sprinted forward (anteriorly) as fast as possible, planting the dominant foot on a force platform set 4.3 meters away from the starting line. They were instructed to plant their dominant foot as hard as possible and change direction off that foot as fast as possible, followed by a backpedal sprint (posteriorly) to the starting line (Figure 3). Following the backpedal sprint, the athlete performed a sport-specific motion (e.g., a ball pass or racket swing) to ensure that the drill mimicked a plyometric practice session. Six repetitions constituted a single AP Drill. Each athlete was instructed "to perform six swings/passes," so they could maintain focus on the sport-specific movement rather than the force platform.

2.4 Shoe Closure Conditions

Within each round of the four movements, the athlete wore an Adidas Adizero Ubersonic 3.0 shoe with one of four different closure designs—Standard Closure and three adjustable tension closures created by Boa Technology, Inc: Lace Replacement, Tri Strap, and Y Wrap (Figure 4). The Lace Replacement closure is constructed with three equally-spaced Boa Textile Guides with lengths optimised to reduce friction on either side of the U-throat. A Boa L6 eyestay mounted dial pulls the patented TX4 lace through the guides to create shoe tension. The Tri Strap closure has three straps stitched to the shoe upper on the medial aspect of the shoe. The straps are attached to the TX4 lace via three Boa Textile Guides on the lateral aspect of the shoe, and a Boa L6 dial was mounted near the proximal portion of the eyestay to pull the laces through the guides. The Y Wrap closure uses two straps; the first strap originates on the lateral anterior aspect of the shoe and terminates on the medial eyestay line, and the second strap originates on the anterior medial aspect of the shoe and crosses towards the lateral posterior aspect of the shoe. The straps are tensioned using the TX4 lace, which routes around the heel via two Boa Textile Guides and a Boa L6 dial. The presentation order of the four closure designs and the movements were randomised for each athlete.

2.5 Performance Variables

For each movement performed, we measured the Time to Complete Movement using a handheld stopwatch. For each force platform strike within a movement, we calculated six biomechanical performance variables: Ground Contact Time, Peak Eccentric Rate of Force Development (RFD), Peak Concentric GRF, Peak Concentric COM Power, Eccentric Work, and Concentric Work using the procedures thoroughly presented in McLellan et al. (2011). Peak Eccentric RFD and Peak Concentric GRF were calculated with the shear GRF in the LSJ, TDS, and AP

movements and vertical GRF in the CMJ movement, which reflect the directional goal of each movement. All Performance Variables were calculated in Visual 3D (Version v6, C-Motion, Inc, Germantown, MD, USA).

2.6 Statistical Analysis

Changes in each of the seven performance variables were compared to the Standard Closure within each movement. A linear mixed-effects model with the fixed effect of condition (Standard Closure, Lace Replacement, Y Wrap, Tri Strap) and the random effect of subject was used for analysis. This statistical approach permitted all the repeated force platform strikes within a movement to be considered while preserving the ability to make a direct comparison of the alternative closures (Lace Replacement, Y Wrap, Tri Strap) to the Standard Closure without accumulation of Type I error encountered in post hoc multiple comparisons—similar to the Repeated Measures ANOVA. The Standard Closure was parameterised as a fixed intercept, each alternative closure was modelled as a slope coefficient, and each subject as an individual intercept. Models were fit using restricted maximum likelihood (REML) algorithm and p -values for each alternative closure were calculated using the Kenward-Roger first-order approximation, which has been shown to maintain the Type 1 error rate to 0.05 for the model fit (Luke 2017). Prior to performing the analysis, we examined distributions of each variable within each movement and within each subject to ensure that the data met assumptions of normality and homoscedasticity. All analyses were performed using JMP Pro 13 (SAS Institute Inc, Cary, NC).

3. Results

Biomechanical performance outcomes demonstrate that the Tri Strap closure and Lace Replacement closure delivered improvements across movements compared to the standard laced closure. The Y Wrap closure yielded performance improvements and impairments compared to Standard Closure, which were specific to the movement performed.

Across the 31 athletes who participated, we analysed and reported on 1458, 1378, 452, and 409 force platform strikes for the Lateral Skater Jump Repeat (LSJ), Countermovement Jump Repeat (CMJ), Triangle Drop Step Drill (TDS), and Anterior-Posterior Drill (AP), respectively. The first and last force platform strike in each set for each movement were discarded to ensure the analysis of only continuous movement. These totals also account for occasional exclusions for repetitions for when an athlete did not land completely within a force platform during a direction change.

3.1 Counter Movement Jump and Lateral Skater Jump

The performance variables were most sensitive to closure when measured during the two agility-based training movements: CMJ and LSJ. The Tri Strap closure improved 4 of 7 performance variables over the Standard Closure during the LSJ, and 4 of 7 variables during the CMJ. The performance variables affected by the Tri Strap closure were different for each movement, and a larger per cent improvement occurred during LSJ over CMJ. During LSJ, the Tri Strap closure improved Movement Completion Time by 0.3 sec (2.8%), Ground Contact Time by 0.01 sec (3.5%), Eccentric Work by 3 Joules (1.5%), and Concentric Work by 4 Joules (0.5%) over the Standard (Table 2). During CMJ, the Tri Strap closure improved Movement Completion Time by 0.1 sec (1.4%), Ground Contact Time by 0.02 sec (1.8%), Peak Concentric GRF by 26 N

(0.6%) and Peak Concentric COM Power by 94 Watts (0.5%) over the Standard Closure (Table 3).

The Lace Replacement closure improved 1 of 7 performance variables over the Standard during the LSJ, and 1 of 7 variables during the CMJ. During LSJ, the Lace Replacement closure improved Peak Concentric COM Power by 27 Watts (1.4%) over the Standard Closure (Table 2). During CMJ, the Lace Replacement closure improved Ground Contact Time by 0.01 sec (1.5%) over the Standard (Table 3).

The Y Wrap closure improved 3 of 7 performance variables over the standard lace closure during the LSJ and impaired 2 of 7 variables during the CMJ. During LSJ, the Y Wrap closure improved Peak Eccentric RFD by 1800 N/sec (5.4%), Peak Concentric GRF by 17 N (3.1%), and Peak Concentric COM Power by 29 W (3.0%). By contrast, during CMJ, the Y Wrap closure impaired Ground Contact Time by 0.02 sec (1.2%) and Peak Concentric COM by 58 Watts (1.9%) compared to the Standard Closure (Table 3).

3.2 Triangle Drop Step Drill and Anterior-Posterior Drill

Although fewer performance variables were affected during the sport-related triangle drop step drill and anterior-posterior drill, the effects of condition were larger than in the agility-based training movements and verified the findings that Tri Strap and Lace Replacement improved performance while Y Wrap delivered mixed results.

The Tri Strap and Lace Replacement closures improved performance during the TDS drill. During TDS, the Tri Strap closure improved Eccentric Work by 9 Joules (6.7%) over the Standard (Table 4). The Lace Replacement closure improved Ground Contact Time by 0.02 sec (4.5%) and Concentric Work by 7 Joules (3.8%) over the Standard (Table 4). During the AP

Drill, the Lace Replacement closure improved Peak Concentric GRF by 30 N (3.2%) over the Standard (Table 5). Although the Y Wrap closure performed the same as Standard during TDS, the Y Wrap closure impaired Ground Contact Time by 0.02 sec (2.9%), Peak Concentric GRF by 51 N (2.3%), and Peak Concentric COM by 59 Watts (2.7%) compared to the Standard during AP (Table 5).

4. Discussion

We investigated how three alternative closure designs affected biomechanical measures of court-based athletic performance compared to a standard lace closure in a population of high-level court and field athletes. The Tri Strap and Lace Replacement closures delivered performance increases across the movements while the Y Wrap had mixed outcomes. This investigation introduces the use of quantitative biomechanical variables to examine how shoe designs affect performance—a critical factor in functional design.

4.1 Performance Outcomes of the Closure Designs

The Tri Strap closure design provided the most consistent performance improvements across movements, which were likely related to its unique fit capabilities. The improvements occurred in 4 of 7 biomechanical variables in both the laterally directed (LSJ) and vertically directed (CMJ) movements. The Tri Strap allows independent tensioning in each strap across the top of the midfoot. This tensioning ability may influence the mechanical properties of the shoe upper and may increase foot-to-shoe proprioceptive input. Also, the Tri Strap shoe was a consistent favourite among the athletes. Although reporting qualitative data was not within the scope of this investigation, many athletes stated during testing that they felt the Tri Strap performed the best.

Beyond being a comment on comfort, this corresponds well with the finding that an athlete's perception of their performance often matches their actual performance (Sterzing et al. 2009).

The Y Wrap design provided substantial performance improvements during the LSJ, a mix of improvements and declines in the CMJ, and performance declines in the AP drill. Of the closures tested, the strap on the Y Wrap was the longest, and the attachments were positioned closest to the medial and lateral sides of the shoes, which reinforces lateral containment of the shoe upper (McPoil 2000). This reinforcement benefits an athlete during intense side-to-side movements such as the LSJ and could be credited for the improved performance changes. The worsening performance in AP and CMJ could stem from the asymmetric strap interaction on top of the foot, which may not be ideal in the symmetric motions of the CMJ and AP drill.

Despite being the most similar to the Standard Lace closure, the Lace Replacement closure provided performance improvements in one or two biomechanical variables in each movement. The biomechanical variables affected by the Lace Replacement were inconsistent across movements. The primary feature of the Lace Replacement compared to the Standard Closure was the ability to tension the laces across the entire tongue evenly. Although the surface contact area is less than the Tri Strap, similar mechanical and neuromuscular benefits likely occurred.

The performance improvements in this investigation ranged from 0.5 to 5.7% and are notable because they represent the effects of merely changing the shoe worn by the athlete. These performance improvements matched the 0.5 to 5.9% gains in similar CMJ variables reported after multi-week training interventions in high-level athletes (Lamas et al. 2012; Marshall et al. 2012). High-level athletes like those tested in these interventional studies and in our sample train in hopes of seemingly small improvements to gain a competitive edge. If similar

improvements can be achieved solely through a change in closure design, with minimal cost increase and no additional risk for injury (Argus et al. 2011), the benefits of shoe closure design become clear.

4.2 Biomechanical Performance as a Measure of Shoe Design

To our knowledge, this is the first study to use biomechanical variables of athletic performance to evaluate differing shoe upper designs. Most biomechanical performance analyses during court-related movements have been applied to vertical jumping. Because all movements in the current investigation centre on directional changes—both vertically and laterally—we chose to use dependent variables specific to the countermovement jump that were similar to McLellan et al. (2011), which informed our questions on performance.

Biomechanical performance variables were noticeably more sensitive during the two agility-based training movements (LSJ, CMJ) than the two sport-based movements (TDS, AP), and highlights the use of laboratory-based performance testing when examining shoe design. The agility-based training movements were more structured and repeatable than the sport-based movements. In the agility-based training movements, the athlete was limited to move in a single plane of motion, and not distracted by sport-based skills or multiplanar direction changes. The training movement environment allows for much lower variance than sport-based movements and enables a testbed that focuses on the potentially subtle changes affiliated with the shoe design.

The results are robust compared to most biomechanical investigations. We recruited our sample based on an a priori power analysis, and the 31 participants achieved our goal of 85% power. By contrast, most investigations using biomechanical performance range from 10-20

participants taken from a sample of convenience and are not powered appropriately to avoid the “winner’s curse” (Button et al. 2013).

4.3 Influence of Shoe Upper Design on Athletic Performance

This investigation supports the concept that the construction of the shoe upper, which is the interface connecting the foot and the midsole, is critical in creating an environment that leads to better movement strategy and better outcomes in performance. Although the mechanical structure of the shoe lower did not change across the conditions, apparent performance changes occurred. The shoe upper facilitates the foot-to-shoe connection and provides the environment for the foot to operate. It is possible that mechanical factors such as tighter fixation leading to less energy loss affected performance, yet changes in proprioceptive feedback may have also influenced these outcomes. The shoe upper has the largest contact area with the foot of any other part of the shoe (Onodera et al. 2017), and likely influences proprioception in addition to comfort, fit, and mechanical properties. While it is difficult to directly determine if a shoe is aiding an athlete in using their preferred movement path (Nigg et al. 2018), increased proprioceptive feedback should allow for increased awareness of the athlete’s segment motion, and enable more accurate and quickly executed adjustments in their movement.

More work on neuromuscular interaction of the upper with the foot is needed to understand if this may play a role in the change of biomechanical performance measures when altering the shoe upper. This knowledge will inform shoe design to better incorporate how the design of the shoe upper can influence performance. Although analysing electrophysiologic measures was beyond the scope of our investigation, we recommend that they be used to help understand the effects of neuromuscular interaction. This may better enable and support the

ongoing discussion on how shoe design affects peripheral sensory information (Barnes and Smith, 1994; Bishop et al. 2006; Kurz and Stergiou, 2003) as well as movement pattern efficiency, energy transfer, dynamic stability, and muscle fatigue (Reinschmidt and Nigg, 2000).

4.4 Limitations

There are limitations to consider when interpreting this investigation. First, this study was not blinded; both the athlete and the laboratory staff were aware of which shoe design was being tested at all times. This has potential implications for both athlete and tester bias. Athletes may be more inclined to perform better, consciously or unconsciously, in a shoe design that is visually appealing or more comfortable. Tester bias may occur unconsciously, particularly during timing movements with the handheld stopwatch. Second, this study used biomechanical variables to measure performance changes due to shoe upper configuration. This method does not allow us to directly determine if the performance changes are due to mechanical support or changes in neuromuscular input. However, we did minimise the role of potentially confounding factors by ensuring that only the closure configuration was changed. No other components on the shoe upper or shoe lower was altered, and presentation of the closures and movements were randomised for each athlete.

4.5 Conclusion and Future Work

Changes to the shoe upper enhanced athlete performance compared to a standard lace closure configuration in two of the three closure designs tested – Tri Strap and Lace Replacement. The design of this study allowed for the mechanical properties of the shoe lower to remain consistent across the closure designs to examine if an alternative closure could enhance performance. Our

results indicate that alternative shoe closures enhance athlete performance. We hypothesise the mechanisms by which performance improved were improved containment and increased proprioception—both due to the wrapping nature of the closures. These findings suggest that the design and construction shoe upper is essential to consider in athletic shoe design.

Disclosure of interest

Three authors were employed by Boa Technology as scientific consultants prior to conducting the research project presented in the manuscript. Four authors are employed by the University of Denver and received compensation for conducting the research. One author is employed by REP Lab, and did not receive any compensation for conducting the research.

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Figure 1. Frequency of shoe sizes range across the participants in this investigation.

Figure 2. Triangle Drop Step. Athletes moved in a triangular pattern, completing six total force platform hits. The pattern for right foot dominant athletes is as follows: Start in the coloured box, backpedal to force platform 4, return to coloured box, move sideways to the white box, perform a sport-specific movement in the white box, backpedal to force platform 1, return to the white box, perform a sport-specific movement in the white box, and move sideways to the coloured

box. The pattern was reversed for left foot dominant athletes. See text for further details and athlete instructions.

Figure 3. AP Drill. Athletes sprinted anteriorly towards the force platform, where they planted their dominant foot and changed direction (backpedalling) towards the starting line. A sport-specific movement was performed at the start line. Six repetitions of this pattern constituted one set. See text for further details and athlete instructions.

Figure 4. Shoe Closures. Adidas Adizero Ubersonic 3.0 shoes were tested with four closure designs: a Standard Lace closure, Lace Replacement closure, Y Wrap closure, and Tri Strap closure. The shoe lower remained unchanged.

Table 1. Participant demographics separated by sport and total population. Demographics were similar across the four sports included in this investigation.

Population	Age, years mean (SD)	Mass, kg mean (SD)	Height, cm mean (SD)	Shoe Size median (range)
Lacrosse (n=4)	24 (9)	78.8 (6.1)	182 (4)	11 (10.5-11.5)
Rugby (n=14)	24 (6)	86.5 (14.3)	179 (6)	11 (9.5-11.5)
Soccer (n=10)	25 (4)	78.2 (10.4)	180 (5)	10.5 (9.5-11)
Tennis (n=3)	19 (2)	75.6 (6.9)	187 (1)	11 (11-11.5)
Total (n=31)	24 (6)	81.6 (12.0)	181 (5)	11 (9.5-11)

Table 2. Results of the linear mixed-effect model for each dependent variable measured during the Lateral Skater Jump (LSJ). Least Squares Mean for Standard Closure and Least Squares Difference compared to Standard Closure for each of the alternative shoe closures. Variance expressed as Standard Error (SE).

Performance Variable	Main Effect of Closure	Standard Closure Mean (SE)	Lace Replacement Diff (SE)	Y Wrap Diff (SE)	Tri Strap Diff (SE)
Movement Completion Time (sec)	$p<0.001$, $F=14.0$	9.1 (0.4)	-0.1 (0.1)	0.1 (0.1)	-0.3 (0.1)** [2.8% better]
Ground Contact Time (sec)	$p<0.001$, $F=10.1$	0.45 (0.02)	-0.01 (0.00)	0.00 (0.00)	-0.01 (0.00)** [3.5% better]
Peak Eccentric RFD (N/sec)	$P=0.02$, $F=3.4$	26100 (1620)	-400 (600)	1800 (600)* [5.4% better]	-1000 (600)
Peak Concentric GRF (N)	$p<0.001$, $F=8.2$	912 (30)	12 (6)	17 (6)** [3.1% better]	1 (6)
Peak Concentric COM Power (W)	$p<0.001$, $F=6.9$	1830 (58)	27 (11)* [1.4% better]	29 (11)* [3.0% better]	-16 (11)
Eccentric Work (J)	$p=0.01$, $F=3.6$	-154 (9)	2 (1)	-2 (1)*	3 (1)* [1.5% better]
Concentric Work (J)	$P=0.001$, $F=5.4$	-205 (10)	0 (1)	5 (1)*	-4 (1)* [0.5% better]

* indicates statistically significant difference in alternative closure compared to Standard Closure at level $p<0.05$

** indicates statistically significant difference in alternative closure compared to Standard Closure at level $p<0.001$

Table 3. Results of the linear mixed-effect model for each dependent variable measured during the Counter Movement Jump (CMJ). Least Squares Mean for Standard Closure and Least Squares Difference compared to Standard Closure for each of the alternative shoe closures. Grey shading indicates improvement, and the diagonal pattern indicates worsening performance.

Performance Variable	Main Effect of Closure	Standard Closure Mean (SE)	Lace Replacement Diff (SE)	Y Wrap Diff (SE)	Tri Strap Diff (SE)
Movement Completion Time (sec)	$p<0.001$, $F=6.9$	8.7 (0.2)	0.0 (0.03)	0.0 (0.0)	-0.1 (0.0)** [1.4% improve]
Ground Contact Time (sec)	$p<0.001$, $F=11.55$	0.60 (0.03)	-0.01 (0.00)* [1.5% improve]	0.02 (0.00)** [1.2% worse]	-0.02 (0.00)** [1.8% improve]
Peak Eccentric RFD (N/sec)	$p=0.30$, $F=1.2$	109800 (6700)	2200 (2000)	-3300 (2000)	2000 (2100)
Peak Concentric GRF (N)	$p=0.16$, $F=1.7$	2175 (115)	0 (12)	-12 (12)	26 (12)* [0.6% improve]
Peak Concentric COM Power (W)	$p<0.001$, $F=9.4$	3996 (155)	-17 (18)	-58 (18)* [1.9% worse]	94 (19)** [0.5% improve]
Eccentric Work (J)	$p=0.64$, $F=0.56$	-476 (21)	1 (2)	-3 (2)	2 (2)
Concentric Work (J)	$p=0.33$, $F=1.1$	541 (19)	2 (2)	2 (2)	-1 (2)

Table 4. Results of the linear mixed-effect model for each dependent variable measured during the Triangle Drop Step (TDS). Least Squares Mean for Standard Closure and Least Squares Difference compared to Standard Closure for each of the alternative shoe closures.

Performance Variable	Main Effect of Closure	Standard Closure Mean (SE)	Lace Replacement Diff (SE)	Y Wrap Diff (SE)	Tri Strap Diff (SE)
Movement Completion Time (sec)	$p=0.12$, $F=1.95$	19.7 (0.5)	-0.1 (0.2)	0.1 (0.1)	-0.2 (0.1)
Ground Contact Time (sec)	$p=0.01$, $F=3.7$	0.39 (0.01)	-0.02 (0.01)** [4.5% improve]	0.00 (0.01)	0.00 (0.01)
Peak Eccentric RFD (N/sec)	$p=0.12$, $F=1.97$	36060 (2840)	361 (1360)	-1870 (1370)	-1540 (1460)
Peak Concentric GRF (N)	$p=0.32$, $F=1.18$	1043 (34)	29 (17)	-21 (17)	-7 (18)

Peak Concentric COM Power (W)	$p=0.82$, $F=30$	1603 (71)	-7 (27)	-20 (27)	5 (30)
Eccentric Work (J)	$P=0.03$, $F=3.1$	-165 (9)	0 (4)	2 (4)	9 (4)* [6.7% improve]
Concentric Work (J)	$p=0.08$, $F=2.3$	178 (7)	-7 (3)* [3.8% improve]	-1 (3)	1 (3)

* indicates statistically significant difference in alternative closure compared to Standard Closure at level $p<0.05$

** indicates statistically significant difference in alternative closure compared to Standard Closure at level $p<0.001$

Table 5. Results of the linear mixed-effect model for each dependent variable measured during the Anterior-Posterior Drill (AP). Least Squares Mean for Standard Closure and Least Squares Difference compared to Standard Closure for each of the alternative shoe closures.

Performance Variable	Main Effect of Closure	Standard Closure Mean (SE)	Lace Replacement Diff (SE)	Y Wrap Diff (SE)	Tri Strap Diff (SE)
Movement Completion Time (sec)	$p=0.59$, $F=0.63$	23.9 (0.6)	0.0 (0.1)	-0.0 (0.1)	-0.1 (0.1)
Ground Contact Time (sec)	$p=0.10$, $F=2.10$	0.45 (0.02)	0.00 (0.00)	0.02 (0.01)* [2.9% worse]	-0.01 (0.01)
Peak Eccentric RFD (N/sec)	$p=0.74$, $F=0.42$	70940 (4000)	-40 (1790)	-1840 (1740)	1020 (1790)
Peak Concentric GRF (N)	$p=0.001$, $F=5.52$	916 (35)	30 (14)* [3.2% improve]	-51 (13)** [2.3% worse]	18 (13)
Peak Concentric COM Power (W)	$p=0.06$, $F=2.5$	1451 (48)	20 (22)	-59 (22)* [2.7% worse]	19 (22)
Eccentric Work (J)	$p=0.77$, $F=0.38$	-226 (12)	2 (4)	-4 (4)	0 (4)
Concentric Work (J)	$p=0.42$, $F=0.95$	177 (7)	4 (3)	0 (3)	-4 (3)

* indicates statistically significant difference in alternative closure compared to Standard Closure at level $p<0.05$

** indicates statistically significant difference in alternative closure compared to Standard Closure at level $p<0.001$