Design and build of a portable apparatus for measuring lace tension

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ABSTRACT

Laces have traditionally been used to secure the foot, limit slippage, enhance fit, and prevent injury across different types of footwear. Quantitatively assessing the merits and effectiveness of laces is technically challenging due to the lack of portable instrumentation that can measure lace tension reliably. Therefore, the purpose of the study was to design and build a portable apparatus to quantify lace tension to be used on footwear in both laboratory and real-world environments. The apparatus was designed to meet three major design criteria: (i) portable, (ii) able to accommodate different types of footwear, lace materials, and lacing patterns, and (iii) able to measure lace tension while the footwear is secured on the foot. As a result of the design process, the apparatus consisted of a base, fabricated from High Density Polyethylene (HDPE), and a frame, made from aluminum and 3D printed Acrylonitrile Butadiene Styrene (ABS). A measurement system was affixed to the frame and consisted of a lever, a non-deformable cable with a hook, a load cell, a caliper, and a microcontroller to measure the force and change in length of laces when a force was applied. The total height and weight of the apparatus was 25.5 cm and 6.35 kg, respectively. A reliability analysis was conducted using three different types of laces (waxed, non-waxed, and carbon fiber blend) and revealed a high internal consistency within lace types with alpha values of 0.95, 0.81, 0.91, respectively. The interclass reliability coefficient across lace types revealed an alpha value of 0.84. As a result of the design, build, and reliability analysis, the apparatus was able to provide reliable measurements of lace tension while satisfying the design criteria. It is envisioned that the apparatus can be used for ongoing investigations across different types of footwear and different types of laces.

Keywords

footwear, lace tension, portable instrumentations

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Introduction

Footwear is the vehicle by which mechanical function is translated to human motion. Various practices including laces, buckles, clips, Velcro straps, and more recently specialized dial systems, have been utilized to secure footwear on the foot, limit slippage, enhance fit, and prevent injury (Frey, 2000; Hong et al., 2011; Werd, 2010). Despite their importance, research investigating the merits and effectiveness of these practices is limited (Sun et al., 2020). Most studies have focused on the effect of lacing techniques on human motion using a combination of motion capture systems, pressure insoles, imaging systems, and the user's subjective assessment of comfort and experience (Hagen & Hennig, 2009; Hong et al., 2011; Myers et al., 2022).

Previous research has provided proof of concept that laces can help limit foot-shoe movement and achieve better fit (Hong et al., 2011). Hagen et al. (2010) revealed a positive relationship between user perceived comfort and stability levels and lace tightness, specifically around the navicular area at eyelets 6 and 7. Hagen & Hennig (2009) as well as Hong et al. (2011) have also reported that different lacing techniques and shoe fit can affect foot pronation and pronation velocity and further reduce injury potential. Myers et al. (2022) also reported a significant reduction of foot-shoe motion during dynamic movements with higher lace tension. Although motion of the foot within the footwear assessed could have been a result of multiple factors, not solely lace tension; frictional injuries are primarily caused by the foot moving inside the footwear.

A recent study by Haque et al. (2022) developed a novel, wearable device, referred to as a Smart Lacelock device, to keep an Inertial Measurement Unit (IMU) in place during kinematic analysis. The device consisted of an IMU and a lace tension sensor. The temporal lace tension measured by the lace tension sensor was used as a metric to ensure the IMU remains in place during use. Results revealed that the device provided a secure and reliable attachment of the IMU to the footwear, and the lace tension sensor provided lace tension measurements that were a representation of the compression force of the lace on the foot.

Quantitatively assessing the merits and effectiveness of lace locking practices is technically challenging. Most measurement instrumentations lack portability or the ability to collect direct and reliable measurements across various types of footwear and laces while the footwear is secured on the foot. Due to the limitations, a portable apparatus was proposed as a potential solution to provide lace tension measurements while the footwear is secured on the foot. The purpose of the study was to design and build a portable measurement apparatus to quantify lace tension of footwear in both laboratory and real-world environments. Furthermore, to assess the reliability of the apparatus across the material properties of different types of laces.

Experiment #1: Design and build of measurement apparatus

The intent was to design an apparatus specifically for the purpose of quantifying lace tension. The design criteria included: (i) portable, (ii) able to accommodate different types of footwear, lace materials, and lacing patterns, (iii) able to assess lace tension while the footwear is secured on the foot.

The base and frame of the apparatus were designed to facilitate data collection on different types of footwear (see Figure 1). The overall dimensions of the apparatus were 25.5 cm in height and 6.35 kg in weight. The base of the apparatus was fabricated from anti-slip HDPE. The footprint was 15.88 cm by 24.13 cm and designed with a platform and a slot to accept different types of footwear (e.g., running shoes, hiking boots, ski boots, ice skates). Adjustable stoppers were installed in the front and on the two sides of the base to limit movement of footwear and ensured consistent alignment of footwear across multiple measurements.

The frame of the apparatus was made from aluminum and 3D printed ABS and was built to house the measurement components. These included a lever, a non-deformable metal cable with a hook at one end, a load cell, a caliper, and an ESP8266 microcontroller (see Figure 1). The lever was used as a mechanism to apply a manual load, and the non-deformable metal cable with a hook was used as a medium to connect the lever to the lace and transfer the applied load to the lace. The load cell was used to measure the force of the load applied to the lace, while the caliper was used to measure the change in length of the lace when the load was applied. The microcontroller was loaded with a program developed in Arduino (Arduino LLC, Boston, MA) to manage the initiation and stoppage of data collection and to collect data from both the load cell and the caliper.

The load cell was calibrated with a known weight to provide confidence in the measurements and to obtain a conversion factor from the unitless analog measurement to a digital force measurement with a meaningful unit (N). The calibration of the load cell provided a conversion factor of 4.69E-5 (N) and a tare value of 25668.8. The caliper was zeroed each time the system was reset.

Data analysis

Output measures of the apparatus included force (N) and displacement (mm) collected by the load cell and the caliper when a force is applied to the lace. To facilitate this, the hook secured to the end of the cable was attached to the lace at the desire eyelet location. Once a force was applied to the lever, the force was transferred to the lace via the cable and pulled the lace away from the tongue of the footwear. The ESP8266 microcontroller was connected to both the load cell and the caliper as a power source and to initiate each collection while recording the measurements of the forces applied (N) and the change in length of the lace (mm). Data collection was initiated and stopped once applied forces of 1.14 N and 10.51 N were reached, respectively. The displacement data is representative of a tension response, commonly referred to as the looseness/tautness in lace tension; therefore, by measuring the displacement of the pull, the apparatus has the potential to provide a meaningful metric for lace tension at a given pulled force.

Experiment #2: Assessment reliability of apparatus

The reliability of the apparatus was assessed using a single-subject repeated measures experimental design. A rigid athletic footwear was laced with three different types of laces (waxed, non-waxed, and carbon fiber blend) to investigate the reliability of the apparatus. The participant was seated with knees flexed at 90 degrees. The apparatus was placed on a flat surface in front of the participant. The participant secured footwear to the right foot with lace tied at their desired tension. The foot was then secured in the apparatus with the skate blade placed in the slot and the adjustable stoppers to limit any movement. Thirty repeated trials were completed. Measurements of the force applied (N) and the displacement of the lace during the pull (mm) were collected for each type of lace at the location of the sixth eyelet, counting from the toe of the footwear.

Data analysis

The force and displacement data were collected within a force range determined by the applied force rate and the sampling rate of the load cell. As a result, each trial consisted of a different number of data points. To standardize the measurements for the purpose of comparisons across trials, a force (N) versus displacement

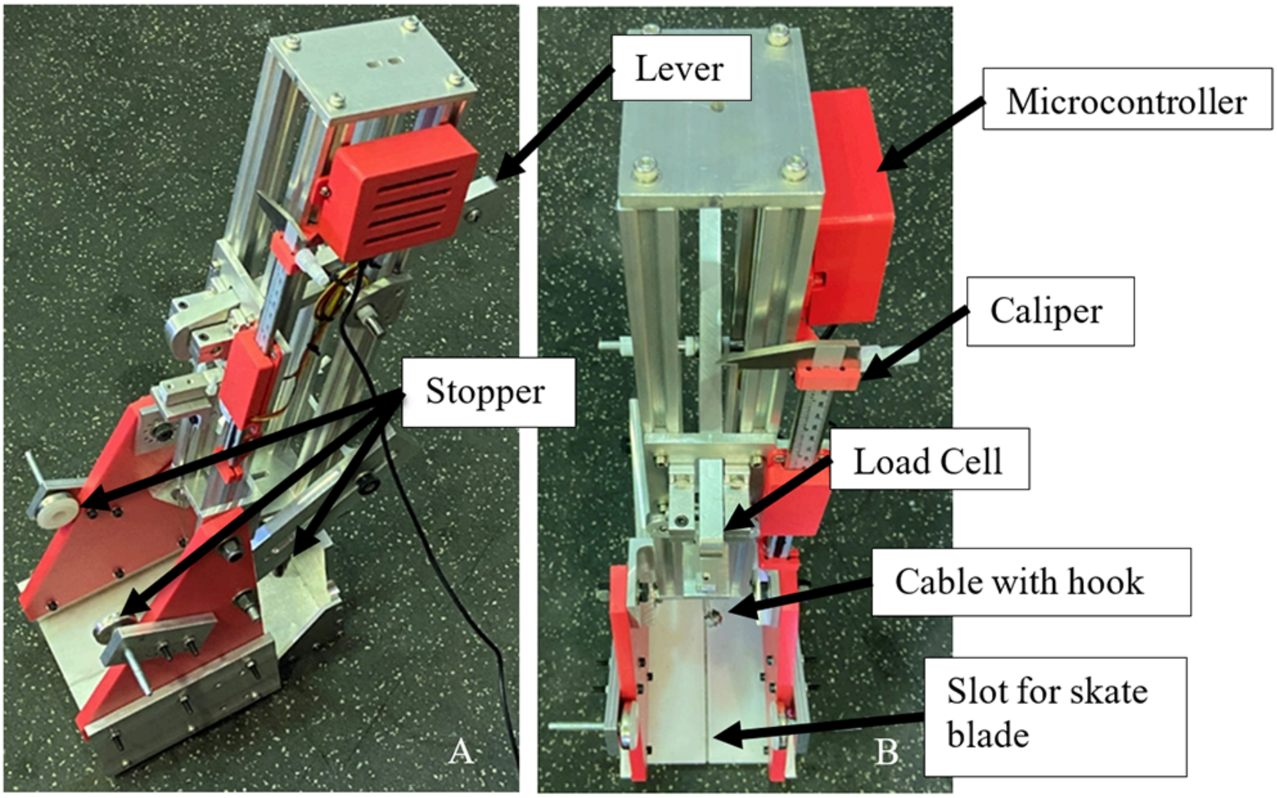

Figure 1 Different views of the apparatus. (A) View at 45 degrees (B) Frontal view. The base of the apparatus was designed to secure all types of footwear including ice skates. There are adjustable stoppers located at the front and the two sides of the base. There is a slot in the middle of the base plate which can allow skate blade to fit in to provide constrain to footwear movement. The lever on the top coming out of the back provided a loading mechanism through the cable while the load cell and caliper attached at the other end measure force and displacement of the force applied respectively. The microcontroller was used to initiate and stop the data collection while recording measurements from the load cell and the caliper.

(mm) plot was generated for each trial. A line of best fit was fit to the data of each trial with the slope of the line representing the stiffness property of the lace, and the y-intercept representing the shift in displacement (mm) of the lace during each trial. The shift in displacement (mm) was used as a comparison value for the lace tension parameter.

Descriptive measures, including the mean, standard deviation, and variance of the measurements, were calculated for each type of lace. A reliability coefficient was then calculated by using linear interpolation to obtain displacement measurements at 5 N, 7.5 N, and 10 N of force for all thirty trials of each type of lace. Cronbach's alpha was used with the estimated displacements from linear interpolation to determine the internal consistency of these measurements. Cronbach's alpha was performed on the measurements of all three types of laces individually and combined to provide an overall interclass reliability coefficient.

Table 1
A linear line was fitted to the displacement (mm) and the force (N) measured by the apparatus. The horizontal shift in the trendline was used as a comparison value for a lace tension parameter. The mean, standard deviation, and variance of the horizontal shift of the trendlines were calculated from thirty measurements of three different types of laces.

Lace Type	Horizontal Shift (mm) (*M* ± *SD*)	Within Variance of Horizontal Shift (mm)
Waxed	52.02 ± 2.41	5.79
Non-Waxed	49.44 ± 1.01	1.02
Carbon Fiber Blend	49.05 ± 1.47	2.16

Results

Descriptive measures (*M* ± *SD*) of horizontal shift and within variance of horizontal shift are illustrated in Table 1. For waxed, non-waxed, and carbon fiber blend lace, respectively.

Cronbach's alpha values for the waxed, non-waxed, and carbon fiber blend laces are 0.95, 0.81, and 0.91, respectively. The results indicated high internal consistency for all measurements across the three types of laces assessed independently. A high overall interclass reliability coefficient with a value of 0.84 was revealed.

Experiment #3: Assessment of lace material properties

Material properties, specifically the stiffness parameter (force/strain) of three different types of footwear laces (waxed, non-waxed, and carbon fiber blend) was assessed using the apparatus. The non-deformable metal cable of the apparatus was also assessed to provide a control measurement (see Figure 2).

In experiment #3, the laces were being assessed independently as opposed to installed in the footwear, therefore the apparatus was configured in a setup similar to a horizontal tensile test (Figure 3). The base of the apparatus was removed along with the non-deformable cable and the hook. Two clamps were added as anchors for the laces; one at the end where the base was, the other attached to the load cell. The load cell measured the force (N), and the caliper measured the elongation (mm) when a tensile load was applied to the lace.

Figure 2 Different laces used for stiffness and reliability assessment. From left to right: carbon fiber blend, non-waxed, waxed, and the cable of the apparatus.

Data analysis

The elongation (mm) was used to calculate strain (% elongation). The measured force (N) and the calculated strain (% elongation) were plotted for each lace for visual comparison. The slopes of the trendlines were used as the stiffness measurement that was correlated to the Young's modulus of each lace assuming minimal deformation for the cross-sectional area of the lace during tensile testing.

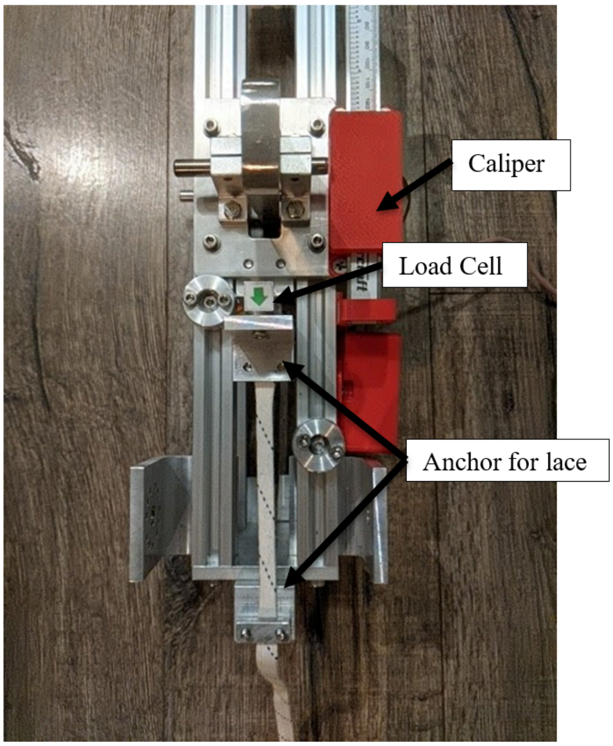

Figure 3 Setup of the apparatus during lace stiffness assessment. The lace illustrated was the non-waxed lace.

Results

The results of the stiffness assessment for waxed, non-waxed, and carbon fiber blend laces, as well as the cable (control) were plotted with measured force as a function of elongation (see Figure 4). The slope of each line represented the stiffness property of each lace. The steeper the slope, the higher the stiffness. A visual comparison of the plots seemed to suggest that the waxed and non-waxed laces had similar stiffness properties that indicated that waxed and non-waxed laces would behave similarly and undergo similar elongation under a tensile force. The visual comparison of the plot also suggested a significant higher stiffness for the carbon fiber blend lace comparing to the other two laces which indicated that under the same tensile force, carbon fiber blend lace would stretch less than the other two laces assessed.

Discussion

A portable measurement apparatus was designed, built and reliability assessed to quantify lace tension across different types of footwear and different material properties of laces. The apparatus was designed to accept different configurations of footwear; for example a cross country ski boot vs. a skate boot with a blade. This flexibility allows for the collection of simple lace tension measurements to examine changes in lace tension pre and post activities when the footwear is secured on the foot. It was acknowledged that not all footwear uses the same type of laces, hence the need to assess different types of laces. Therefore, the apparatus was also capable of measuring reliable tension across laces with different material properties, and had the sensitivity to recognize and characterize the differences in lace stiffness properties.

Laces are one practice used to secure the foot in footwear, limit slippage, enhance fit, and prevent injury. These functions of the laces are crucial to the performance of the footwear. Although previous studies have identified the function of laces, not all laces have the same effectiveness in securing the foot inside the footwear. Laces are made of different materials with different stiffness properties and therefore, behave differently under load. The stiffer the material, the less tendency for the material to stretch under a tensile load. Furthermore, lace tension is not always maintained during an activity. If laces loosen, the performance of the footwear can be compromised and potentially contribute to injury (Hagen & Hennig, 2009; Hong et al., 2011). Instrumentation that can provide a metric for lace tension and feedback on lace behavior can help identify the contribution of lace tension to footwear performance, foot kinematics and the mechanics of injuries.

Previous studies (Hagen & Hennig, 2009; Hong et al., 2011) have investigated the relationship between different lacing patterns or techniques used in lacing, and their effects on human motion and shoe fit. However, these studies did not directly assess lace tension. In contrast, the apparatus developed in the current study

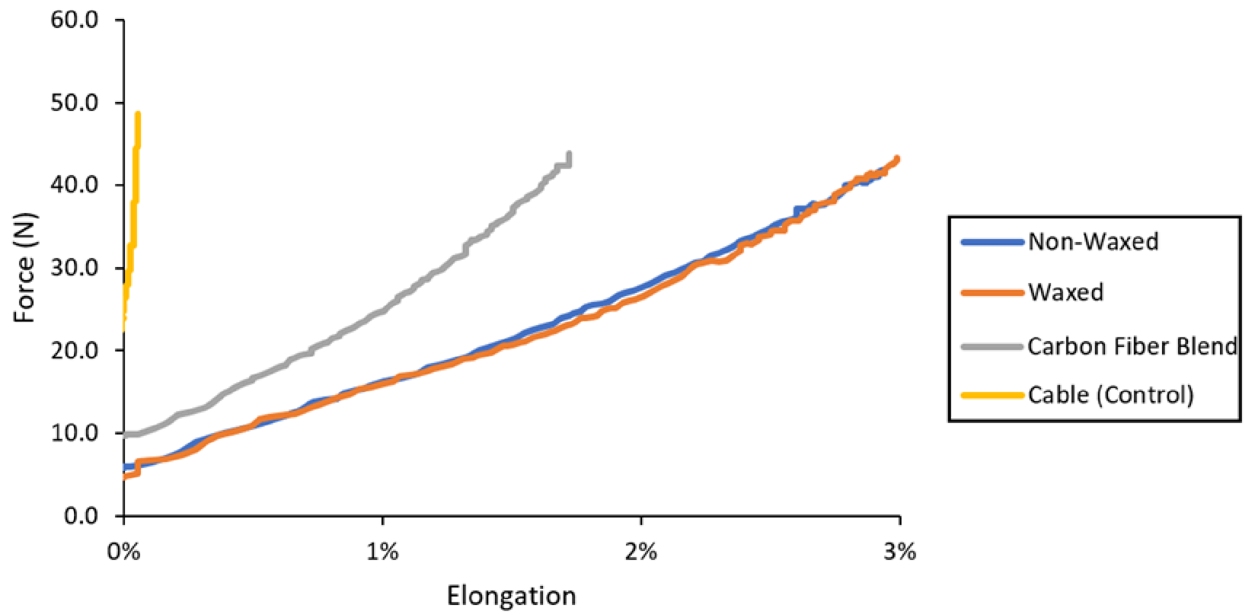

Figure 4 Force (N) vs. strain (% elongation) plot of stiffness across different types of laces. The slope of each line represented the stiffness parameter (force/strain). The steeper the slope the stiffer the material meaning the material is less likely to stretch when a force is applied.

allowed for direct assessment of lace tension at different eyelet locations across various lacing patterns. This provides valuable information on the looseness/tautness around different regions of the foot. By linking these tension variations to human motion and shoe fit, the apparatus can provide a deeper understanding of the role of laces in footwear.

The footwear selected for the purpose of assessing reliability was representative of rigid athletic footwear with multiple eyelet locations. The apparatus provided comparative measurements for pre and post activities while wearing the same footwear. Although the apparatus was designed to assess lace tension across different footwear types, future research will be required to investigate the generalizability across footwear. However, it is believed that the reliability of the apparatus will be maintained across footwear types and designs.

The experimental apparatus designed was a first generation build and thus, has some limitations. The apparatus is portable, but not wearable; therefore, it cannot provide temporal measurements. It can only provide measurements for comparison, such as pre and post an activity. The apparatus collected data when a manual load was applied. The data points are collected based on the sampling rate of the load cell and the manual loading rate. Finally, the load cell used for the purpose of the build was a strain gauge-based load cell, so drift can occur and needs to be taken into consideration during analysis.

In summary, the study presents the design, build, and assessment of a portable lace measurement apparatus. The apparatus provided researchers with a reliable measurement of lace tension and differentiated between materials properties of different types of laces. Overall, the apparatus could serve as a measurement device to help researchers and practitioners gain further understandings related to the contribution of footwear to performance versus potential of injury across different types of footwear.

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Competing interests

The authors have declared that no competing interests exist.

Data availability statement

All relevant data are within the paper.