Using a Pilot Study to Establish Experimental Methods for Inexpensive Instrumented Insoles used in Dynamic Skiing Analysis

Dr. Andrew Peter Vogt[1] *IEEE Member*, Abhijit Boppana[2], and Dr. Stacy J. M. Bamberg[3] *IEEE Member*

Abstract— **Loss of balance leads to increased likelihood of falling for human locomotion. Determining the likelihood of falling for skiing locomotion is challenging because, unlike walking, normal locomotion is not clearly defined. One of the first learned styles of skiing is wedge style (WS). WS affords relatively easier balancing and speed control due to a wide base of support and greater resistance to forward movement, respectively. As skiers become more familiar with WS, their sensory, cognition, and actuation improve and they are able to apply more advanced styles, namely parallel style (PS), which requires refined balance. This paper studies the effects of WS and PS, on a single subject pilot study, and how they effect the likelihood of falling. A traditional laboratory setting was not suitable because of extreme difficulty and expense required to mimic the environment. Specially designed instrumented insoles were used to capture force data in a mountain environment.**

I. INTRODUCTION

Skiing equipment and ski theory is always changing. Professional ski instruction organizations, e.g., Professional Ski Instructors of America, frequently reorganize theories to better teach clients and other professionals. Properly supporting bodyweight allows efficient management of forces, primarily friction and normal forces, to control speed and direction. There are nearly infinite inverse kinematics (ways to move the body) to control ski forces. Maximizing efficiency, which to a large extent implies the skier has a low likelihood of falling, is a great challenge.

Skiing is relatively complex and has been described as a rhythm encompassing balance, finding support, and gliding [1]. Even for accomplished athletes, locomotion that effectively encompasses all these aspects takes years to refine. Quantified motion analysis helps to better understand the complexities of human locomotion. However, traditional motion capture laboratories cannot be used for skiing because they cannot effectively recreate the environment. Instead, wearable instrumentation can quantify motion in an established controlled mountain environment (e.g., a ski resort).

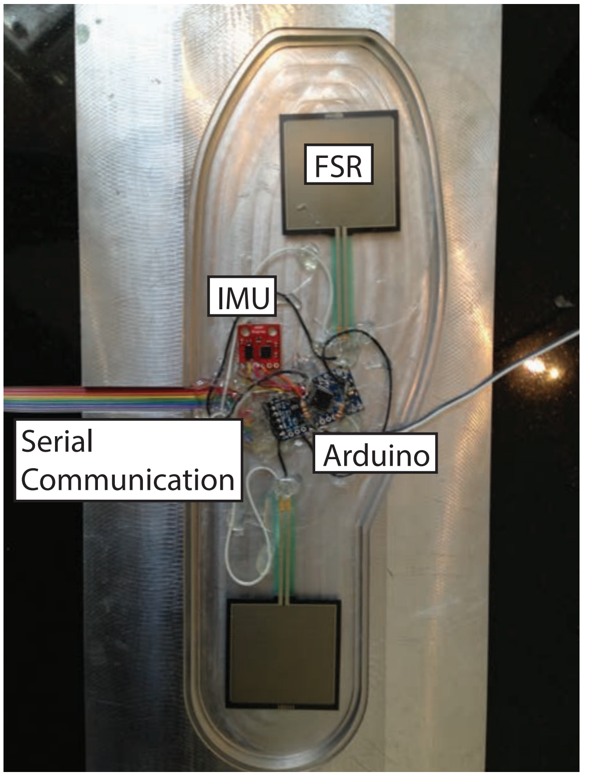

Fig. 1: Photograph of equipment used in instrumented insoles before pouring the mold. Unlike Fig. 2, where the Vibrotactile Motors (VMs) are embedded in the insole, this particular design tethers one VM out of the insole to be placed between the ski boot cuff and skier's shin.

Wearable instrumentation has allowed skiing studies to drastically improve within the last few decades. Farrario *et al.* used a Fourier Analysis to predict trajectories of skiers. They found trajectories of professional skiers, who take the same run under the same conditions, to have more repeatable results compared to casual skiers [2]. Coaches and scientists have instrumented skiers to get a better understanding of all of their intricate motions [3], [4], [5], [6], [7]. Some have used these tools to provide advanced feedback between students and coaches [3], [5], [6]. However, these systems are costly, prohibiting wide adaptation.

While using skiing as the method of locomotion, this work is primarily motivated toward better understanding the likelihood of falling during human locomotion. Comparing skiing studies to prior work on walking studies [8] provides a means to understand the likelihood of falling for generalized human locomotion. Unlike costly systems mentioned above, each insole can be fabricated for less than 200 U.S. dollars and could provide this valuable information to many skiers.

The remainder of this report covers Hardware and Software Development, the Original Experimental Methods, the

---

*This work is supported by Salt Lake Community College and the University of Utah

[1] A. Vogt is Faculty of Engineering at Salt Lake Community College in Salt Lake City, Utah, USA `andrew.vogt@slcc.edu`

[2] A. Boppana is an undergraduate student of Mechanical Engineering at the University of Utah in Salt Lake City, Utah, USA `abhijit.boppana@gmail.com`

[3] S. J. M. Bamberg is Faculty of Mechanical Engineering at University of Utah in Salt Lake City, Utah, USA `sjm.bamberg@utah.edu`

Pilot Study, and Revised Experimental Methods (as a result of the Pilot Study) which are used in other analyses.

II. HARDWARE AND SOFTWARE DEVELOPMENT

The pilot study resulted in instrumented insoles to measure foot kinetics and kinematics. Other devices, such as skis or bindings, could have also been instrumented. However, the instrumented insoles had the advantage of being more transferrable to other skiers or ski equipment (a requirement of this study), they were inexpensive, and were protected from the elements. These insoles consisted of electronics that were placed in a cast, as shown in Fig. 1, and then embedded in blue silicone rubber, as shown in Fig. 2. Both left and right foot insoles, as shown in Fig. 2, were created and used in testing. Fig. 2 shows the original insoles where Vibrotactile Motors (VMs) were embedded in the insole. A later insole iteration, Fig. 1, tethered one VM outside the insole to be placed between the ski boot cuff and the skier's shin.

Contact dynamics were captured using 1.5 inch square force sensitive resistors (FSRs) (Interlink Electronics of Camarillo, California) toward the toe and heel of the foot and a 6-Degree Of Freedom (DOF) digital inertial measurement unit (IMU) (Sparkfun Electronics of Boulder, Colorado) placed in the center of the foot. The FSRs and IMU were fed into analog inputs of an Arduino Pro Mini Microcontroller (ATMEGA 328 3.3V 8 MHz Processor) (Dangi internet Electronics of Spain). Analog inputs of this Arduino read voltage in terms of bits; 0 to 1023 bits linearly correspond to an analog input of 0 to 3.3V. VM actuators were connected to the digital outputs on the Arduino.

Each FSR was connected in series with a 100Ω resistor, which provided an acceptable range of measurement for skiing. Placement of the FSR centroids were approximately 9 in apart to account for an average foot size and independently capture heel and toe kinetics.

The FSRs and actuators were connected to the analog inputs and digital outputs, respectively, on the Arduino microcontroller. The analog input recorded in bits and the digital output produced either 0 or 3.3V. For calibration and testing, the Arduino was connected to the USB port of a laptop computer through a tether of approximately 18ft. Serial communication was used to transmit the data from the Arduino to the laptop at a 115200 baud rate. The FSRs were sampled at a rate of 155 Hz. The Arduino microcontroller was programmed using the Arduino programming environment. All data analysis was postprocessed using MATLAB.

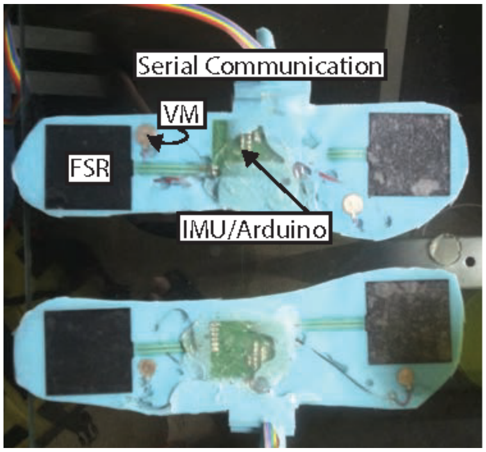

Fig. 2: Photograph of instrumented insoles after pouring the mold. Unlike Fig. 1, a shield was used in the iteration to connect the electronics.

III. ORIGINAL EXPERIMENTAL METHODS

The original proposal had the following specifications:

- Tests would be conducted on clear days with temperatures between 15 and 25 ^{o}F.
- The course would be controlled to be the same slope every time. This was set to be the run on the beginner slope with six cones to define the testing course.
- Skiers would first take three runs within the cones as directed without any feedback. They would then do six runs with vibrotactile feedback, which would be randomized between three runs with a signal that is intended to appropriately cue the skier to shift weight between the left and right limbs, and three runs with a signal that has been constructed to provide random cues.
- Cones would be used to allow some control over both the course and the speed. A demonstration would be given first to indicate the appropriate speed.

IV. PILOT STUDY

The single subject pilot study was conducted with IRB approval (IRB 00055522) from the University of Utah.

A. *Skiing Mechanics and Potential to Fall*

Originally, the skier would receive vibrotactile and visual feedback. The thought was that comparing the two would lead to important conclusions regarding PF. The first iteration of the insole, shown in Fig. 2, had two Vibrotactile Motors (VMs) in the insole: one near the toe and the other near the heel. Before the pilot study, the rear VM would actuate for one second, signaling the skier that the turning signal was coming; one second later, the front VM would actuate for one second; and finally, the process would repeat after 4 s (seconds) elapsed. The expert skier in the pilot study identified that the vibrations in the boot completely dampened the VM signals, even when skiing smoothy with carving locomotion.

Since use of the VMs was not feasible, a new approach was developed to compare basic styles of beginning and advanced skiing; specifically that *individual improvements in skiing mechanics result in decreased likelihood of falling*.

Ski structure helps to explain the mechanics of beginning and advanced skiing styles. The structure of a ski, shown in Fig. 3, consists of tips, tail, top-sheet, base, and edges. Under normal skiing, the tip leads and the tail follows. The top sheet provides the primary structure (i.e., stiffness and vibration damping) of the ski, the base provides a low-friction surface

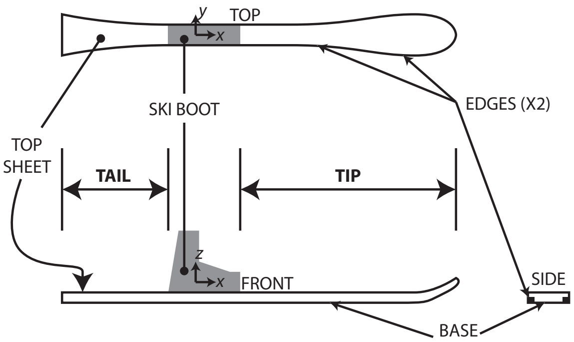

Fig. 3: Structure of a typical ski. The ski boot is placed offset from the center toward the back, which causes the tip length to be longer than the tail.

to allow sliding with contacted snow, and the edges (on both sides) provide a medium to initiate turning and stopping of the ski. The inside and outside edges refer to the two edges closest and furthest to each other, respectively (i.e., the right edge of the left ski and the left edge of the right ski are the inside edges).

In order to maintain speed control, a skier will select an appropriate style based on weather, obstacles, ability, and fall line. Weather can include such factors as temperature, humidity, precipitation, and wind direction; and obstacles can include trees, rocks, other skiers, and varying snow conditions. Ability describes a skier's skill level and experience. Fall line, illustrated in Fig. 5, refers to the direction with the largest gradient in slope; in other words, the direction a ball would roll if placed on the ground.

This study looks at two of the most fundamental skiing styles, as shown in Fig. 4: wedge style (WS) and parallel style (PS). The primary difference is that WS provides a greater resistance to motion of forward skier motion and is thus easier to control. As shown in Fig. 4, in WS, the ski tips have closer proximity than the tails.

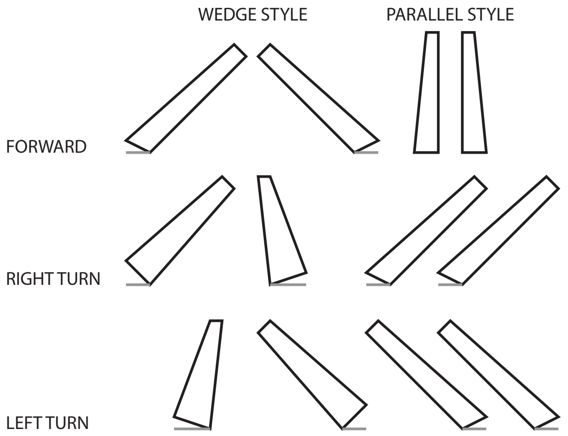

Fig. 4: WS and PS illustrations of both skis traveling straight, right, and left. The small gray line at the bottom indicates whether the inside or outside edges are engaged. PS edging is significantly different than WS and is more difficult for subjects to control.

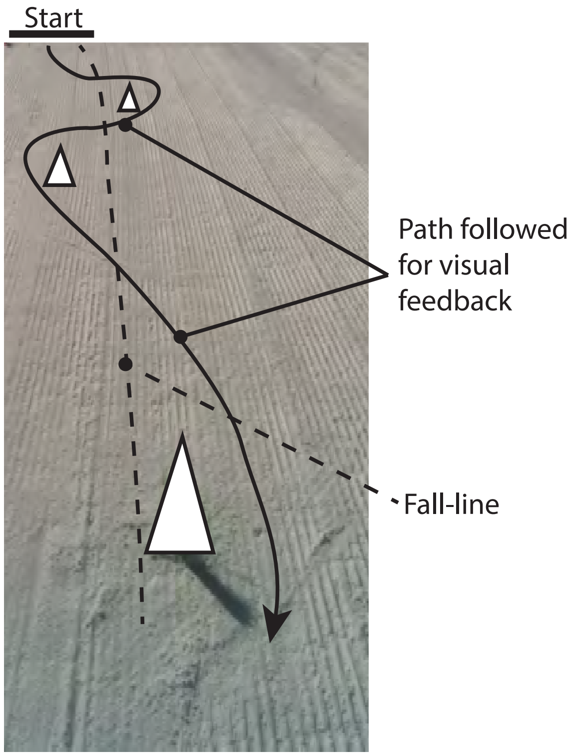

Fig. 5: Path established from testing. This path shows the first three turns. The white triangular markers represent where turning cones were placed. The turning markers help maintain speed control by ensuring the subject crosses the fall-line multiple times.

The greater resistance to motion in WS is primarily due to the constraints from the skier's body. As the skier pushes the feet out to create a wedge shape, both the inside edge angles and resisting surface increase. Even when turning, the inside edges are engaged, maintaining more resistance to motion. Although edge angle from PS can be high, the use of one inside and one outside edge results in much less resistance to motion.

In addition, WS generally provides a much larger base of support due to a wider distribution of the skis across on the snow. In addition to easier speed control, the wedge more effectively resists moments caused by imbalance. This combination helps refine the above hypothesis such that *the mechanics of WS will yield a lower likelihood of falling than PS.*

B. Course Selection

The course was selected to ensure safety of skiers and enable consistent results. Fig. 5 illustrates the first few turning markers of the course, all of which follow the fall line. The course had a slope of 6 degrees, and the markers were spaced 11m apart parallel to the fall-line and 2m apart

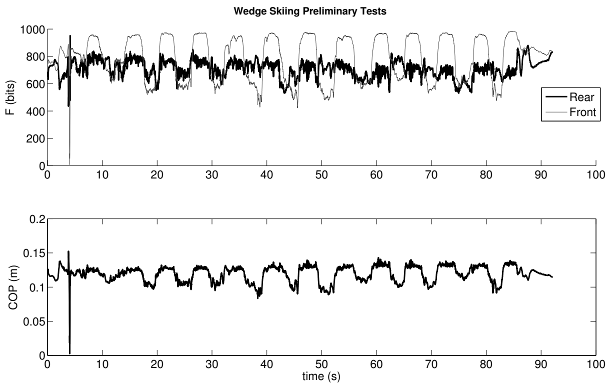

Fig. 6: Preliminary
Wedge Test. The top subfigure illustrates data from the front and rear FSRs. The FSRs had not been modeled for the preliminary tests, so they are expressed in bits directly received by the Arduino microcontroller. The bottom subfigure shows the COP as calculated from the front and rear FSRs.

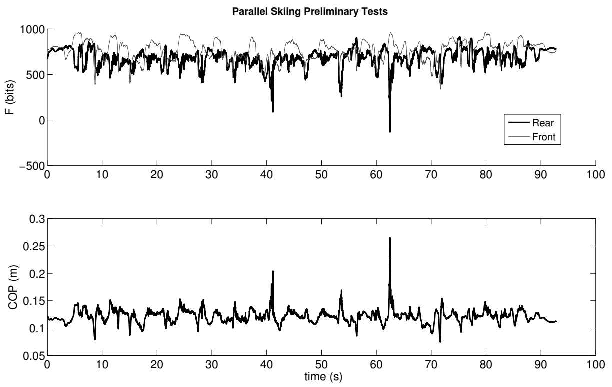

Fig. 7: Preliminary Parallel Test.
The top and bottom subfigures are the same as presented in Fig. 6. The COP for PS appears significantly more stochastic than WS, suggesting a higher likelihood of falling.

perpendicular to the fall line. As illustrated in Fig. 5, the subject skied around the outside of all the turning markers. The temperature was 22^{o}F when the study was conducted (which was within the allowed 15-25 ^{o}F).

C. Pilot Study Results

Sample WS, Fig. 6, and PS, Fig. 7, plots display data gathered from the FSRs. On both plots, the first subfigure shows the actual forces recorded from the front and rear FSR, and the second subfigure shows the calculated Center of Pressure (COP). The reference point of the COP is the center of the heel. When using prior work to identify the likelihood of falling in walking studies, [8] illustrated that low likelihood of falling correlates with periodic motion. With the exception of the first 10 s (where the skier was ramping up speed) WS for both raw FSR and COP illustrates more periodic behavior than PS. Based on prior work, [8], which qualitatively indicated that periodic behavior led to lowered likelihood of falling, this again helps to refine the above hypothesis that *WS will yield a lower likelihood of falling than PS.*

V. REVISED EXPERIMENTAL METHODS

Following the pilot study, a few important changes were made to the original experimental methods to ensure completion of the study. These methods were implemented in a separate study completed approximately three months later.

- Due to lack of sensation, the toe VM was moved out of the insole and tethered so it could be placed between the shin and ski boot cuff. The VMs were still found to be ineffective and their use was discontinued.
- Subject recruitment goal: 12 subjects total, with approximately half being advanced or expert and half being novice or intermediate.
- Air temperature: Recorded for all subjects. Temperatures up to 65^{o}F due to spring testing conditions.
- 1 Baseline test where is the skier is instructed to ski how they are accustomed (no feedback whatsoever).
- 2 WS and 2 PS (4 total) tests where the skier will ski around the outside of the cones, used as visual feedback, as illustrated in the course presented in Fig. 5
- Randomization of WS and PS ameliorated training effects.

VI. CONCLUSION

This article establishes appropriate experimental methods for using instrumented insoles, with the primary intent of determining the likelihood of falling in skiers. The methods outlined in this article have been extended to a multiple-subject study. Further work on a multiple subject test is to be presented in a separate publication.

REFERENCES

[1] S. Loland, “Alpine skiing technique: practical knowledge and scientific analysis,” *Science and Skiing IV*, pp. 43–58, 2009.

[2] V. Ferrario, C. Sforza, G. Michielon, S. Dugnani, and F. Mauro, “A mathematical method for the analysis of trajectories in giant slalom,” *Science and skiing*, pp. 107–115, 1997.

[3] F. Michahelles and B. Schiele, “Sensing and monitoring professional skiers,” *Pervasive Computing, IEEE*, vol. 4, no. 3, pp. 40–45, 2005.

[4] T. Holleczek, C. Zysset, B. Arnrich, D. Roggen, and G. Troster, “Towards an interactive snowboarding assistance system,” in *Wearable Computers, 2009. ISWC’09. International Symposium on*. IEEE, 2009, pp. 147–148.

[5] T. Holleczek, A. Regg, H. Harms, and G. Trster, “Textile pressure sensors for sports applications,” in *Sensors, 2010 IEEE*. IEEE, 2010, pp. 732–737.

[6] P. Schaff, V. Senner, and F. Kaiser, “Pressure distribution measurements for the alpine skier–from the biomechanical high tech measurement to its application as swingbeep-feedback system,” *Skiing and Science. London: E & FN Spon*, pp. 159–172, 1997.

[7] D. Tatsuno, T. Yoneyama, H. Kagawa, N. Scott, and K. Osada, “Measurement of ski deflection and ski–snow contacting pressure in an actual ski turn on the snow surface,” *Science and skiing iV. Meyer & Meyer Sport (UK) Ltd, Maidenhead*, 2009.

[8] A. Vogt, A. Merryweather, K. Beschorner, and S. J. M. Bamberg, “Potential to fall of bipeds using foot kinematics,” in *International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) Conference 2013, Osaka, Japan*, 2013.