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DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

EVALUATION OF A FOOT-MOUNTED SLIP SENSOR

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ABSTRACT

Bipedal robots have become a reality in recent years but still suffer from numerous operational difficulties, many of which concern maintaining balance. As robot locomotion advances, a dynamically stable gait simulating human walking will be a major focus since it permits much quicker movement. Slip during footfall will be a primary concern. Since slip-related falling is a prominent cause of accidental injuries in the United States, the study and measurement of human gait patterns, especially during incidences of slip, have been conducted using varied instrumentation. A novel processing algorithm has been proposed that utilizes an unscented Kalman filter to identify slip events. Evaluation of the sensor required a static test to simulate conditions during stance phase and a dynamic test to simulate conditions during heel-strike. Initial data from the static test indicated the Kalman filter had potential, but the acceleration transients produced from stick-slip motion were not sharp enough to properly identify slip initiation or sticking. Since most falls occur during heel-strike, data from the dynamic test will be a better indicator of the viability of the proposed sensor.

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Chapter 1

INTRODUCTION

1.1 Premise

Foot slippage, a safety concern due to the risks associated with falling, results from too little friction between the foot and the floor during contact. According to the Bureau of Labor Statistics, slip-related falls accounted for over 200,000 non-fatal injuries (US Department of Labor, 2006) and over 80 fatal injuries (US Department of Labor, 2007) in the US in 2005 and 2007, respectively. Injuries over the years have led to research, many times sponsored by insurance companies, into proper ground surface friction coefficients to prevent slip, which can be categorized as either macro- or micro-slip depending on the slip distance. Macro-slip is noticeable and can cause loss of balance whereas micro-slip occurs regularly during normal walking (McGorry et al., 2007) and may occasionally be enough to create a sensation of impending macro-slip. Slip behavior can occur between any two objects in contact and is not witnessed solely during locomotion although that is the current focus.

Research has found that human feet slip during three phases of contact with the ground surface: heel-strike, stance phase, and toe-off (Figure 1). While humans have a sense of balance and can quickly and effectively adjust their center of gravity to prevent or diminish a fall, machinery cannot unless programmed accordingly. Consequently, robots whose locomotion resembles a human gait may fall due to foot slippage.

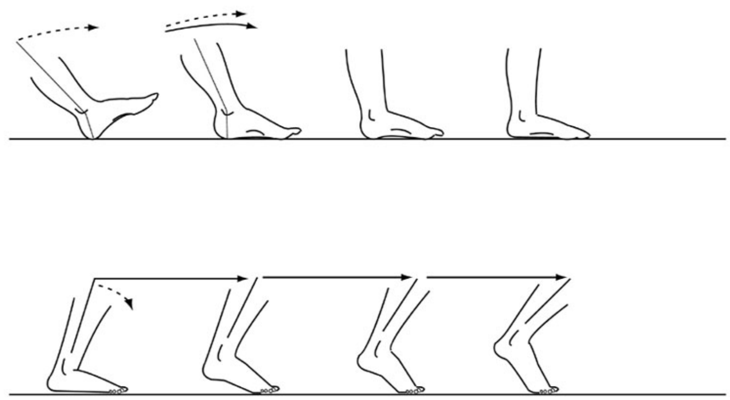

Figure 1 – Physical dynamics of heel-strike.
Source: http://www.leedscarroll.com/Graphics/Tech_Illustration/HeelStrike.shtml

Development of human-like robots has been the object of much discussion, both as a technology and as an ethical dilemma. Current ventures to create a robot with human-like locomotion, such as ASIMO by Honda, have had difficulty maintaining balance during movement. Simple tasks for a human, such as turning, climbing stairs, and walking to name a few, are only just beginning to be able to be accomplished by the most sophisticated robots. More complicated maneuvers will obviously require more complicated controls and sensors, and perhaps even different actuator systems.

Current robot designs cannot achieve quick locomotion due to limitations of statically stable gait, in which the weight of the robot is constantly balanced. This is directly opposite of true human dynamic gait where locomotion is a result of consistently off-balanced steps. Dynamic gait for a robot, however, would present significant challenges to prevent falling, including sensing mechanisms, compensation algorithms, and proper physical adjustments.

1.2 Scope

The purpose of this study is to validate a sensor that detects and identifies slip events. The current sensor design utilizes an inertial measurement unit (IMU) with two accelerometer axes and one gyroscope to measure planar acceleration and angular velocity, respectively. The difference in the measured and predicted acceleration will be minor unless an impact occurs, causing a spike in measured acceleration. Whether or not a spike indicates a slip or non-slip event will be deduced by an unscented Kalman filter (UKF). While the current system consists of an IMU connected wirelessly to a laptop that evaluates the data in MATLAB, eventually this system will be embedded in a sensor that could more realistically fit within a robot foot.

Before the effectiveness of the slip sensor in robot locomotion could be assessed, experiments had to prove the sensor accuracy. Due to the different modes of slip events (sliding versus foot strikes), validation of this sensor requires two distinct testing rigs to be designed and constructed—a static and a dynamic tester. The former design will validate the ability of the sensor to detect sliding on different inclines, similar to stance phase slippage in a human gait. The latter design will validate the ability of the sensor to detect impact slipping events, similar to heel-strike slippage. Slip events resulting from impact occur more often due to the higher forces and accelerations produced.

Chapter 2

LITERATURE REVIEW

2.1 Brief history

Surprisingly, friction has been a topic left relatively unexplored throughout history. The three initial laws of friction were all established before 1800 and have changed little since then. Da Vinci and later Amontons (1690s) independently stated that for one solid body sliding over another the frictional force is proportional to the load and independent of the area of contact. Coulomb (1785) later added that frictional force is independent of sliding velocity. A modification to this third law was proposed by Morin (1835) that implemented a kinetic and static coefficient of friction dependent on the motion, or lack thereof, of the two surfaces in contact. Recent studies have shown that while the first two laws are generally true with minimal error, the third law, and even to an extent its later modification, is incorrect (Rabinowicz, 1956).

Blok (1940) found that the stick-slip amplitude becomes smaller as the velocity is raised and attributed this to the dependence of the static coefficient on the time of stick. Later work verified this hypothesis (Dokos, 1946). Similarly, the kinetic coefficient was seen to vary with velocity even with smooth sliding. Measurements of displacement-time function of a rider during slip were used to calculate a friction-velocity curve by Sampson et al. (1943). Building on the work of Blok (1940), Dokos

(1946), and Sampson et al. (1943), Rabinowitz (1958) proposed that the kinetic coefficient is not only velocity dependent, but also displacement dependent. This critical distance concept implies that a memory effect of previous sliding history characterizes current kinetic coefficient values rather than the velocity itself.

This concept also suggests a simple relation between static and kinetic coefficients, which explains their equivalence at very small stick times. It is logical then to consider that static friction does not exist as such and is rather slipping at very low velocity (Bristow, 1950). For an object at rest, the weight of the object itself can be sufficient to produce very low velocities, on the order of one foot/year for lead, driven by the shear forces from creep. These shear forces depend greatly on the material elasticity of the objects.

2.2 Stick-slip

Studies of friction have shown that when one of the sliding surfaces has an appreciable degree of elastic freedom, the motion may not be continuous but rather a series of jerks (Bowden, 1945). This frictional phenomenon is known as stick-slip and can result in sound such as the squeak of bearings or a grating scratch of chalk on a blackboard. Literature suggests that the introduction of external damping, the application of a lubricant, and the stiffening of the spring can all eliminate unwanted stick-slip events (Rabinowicz, 1958); however, in the current evaluation stick-slip is desired due to the multiple acceleration transients it can produce. Also, the bulk motion will ease visual identification of slip events from the acceleration traces. This would indicate that an undamped, highly elastic, and dry system would most likely promote stick-slip behavior. Data, however, indicate that a dry system may not always be ideal for such behavior since clearer stick-slip events occurred with lightly wetted surfaces, perhaps as a result of increased sticktion.

2.3 Identification of Slip

The high incidence of slip-related injuries has led to recent studies of tribologic properties of shoe heels and soles, flooring materials, and interactions at the shoe-floor interface. A majority of the investigations have utilized various slip meters to measure the coefficient of friction (COF) but the results often vary greatly on experimental factors, such as the speed of impact of shoe material with the floor, thickness of contaminant film (Grönqvist, 1999), and width of tread grooves on the heel of a shoe (Li and Chen, 2004). The number of factors renders the comparison difficult.

Other investigations have focused on a simulation of slip events to better represent human gait and actual footwear. While conditions are better replicated, the complexity is inherently more complex due to the addition of human factors. Both McGorry *et al.* (2007) and Gill and O'Connor (2003b) found it necessary to split up the participants into separate groups based on accelerations at heel strike for equal walking speeds. The displacement of the heel after heel strike, known as the slip distance, is often a reliable tool to assess COF, and with COF to assess the possibility of slip. For normal walking speeds, Redfern *et al.* (2001) reported required COF in the range of 0.17 to 0.20.

Due to the difficulty in measuring small heel movements outside of a laboratory setting, accelerometers have been used in human-centered approaches to study the body kinematics during motion. While some literature has successfully evaluated the measurement of slip events using an accelerometer mounted to the trunk (Hirvonen et al., 1994), the current focus is on slip detection from heel-mounted accelerometers. A study of the acceleration during foot fall for 21 individuals at different speeds and different floor surfaces indicated a reasonably strong relationship between slip distance, determined by the maximum displacement of the heel, and deceleration time, determined from the initial zero crossing of forward acceleration (McGorry et al., 2007). It was also observed and previously indicated that the individuals were segregated into three groups dependent on mean slip distance of an individual over all test runs.

There are three distinct slip classifications—non-slip, micro-slip, and slide—but a standardized classification scheme has not yet been clearly established in literature and several authors use varying slip distance values. A normal gait containing no slip events can still incur slip distances of 1.8 mm (Chambers et al., 2003) , < 3 mm (Cham and Redfern, 2002b), and < 4 mm (McGorry et al., 2007). Micro-slips can occur during normal gait yet are not perceptible to the individual and have been reported at 10-20 mm (Perkins and Wilson, 1983) and < 30 mm (Leamon and Li, 1990 and McGorry et al., 2007). Between micro-slip (~ 30 mm) and slip resulting in a loss of balance (90 – 100 mm), the heel tends to slide thereby disturbing the gait pattern.

2.4 Review of friction tester devices

The construction of an accurate and repeatable friction tester has been a focus of numerous projects. Chang et al. (2001) outlines most friction testers related to human-centered assessment to date and offers comparisons of their characteristics. Several devices are offered here but Chang et al. (2001) covers many more devices in greater detail.

Horizontal Pull Slipmeter: It is based on the static drag-sled and uses a motor to drag a weight across a surface. The device is intended for use on dry surfaces only.

Figure 2 – Example of a Horizontal Pull Slipmeter (HPS), a drag-sled-type device.
Source: Chang et al. 2001

Portable Articulated Strut Tribometer: It loads a friction coupon onto a base material, increasing the angles of the loading strut until slip occurs. The tangent of the angle is the COF.

Figure 3 – Example of a Portable Articulated Strut Tribometer (PAST).
Source: Chang et al. 2001

The Sigler: It measures the energy loss of a pendulum swiping across a floor surface. Due to the short dwell time on the surface, it does not suffer the same difficulties of adhesion as other drag-type slipmeters.

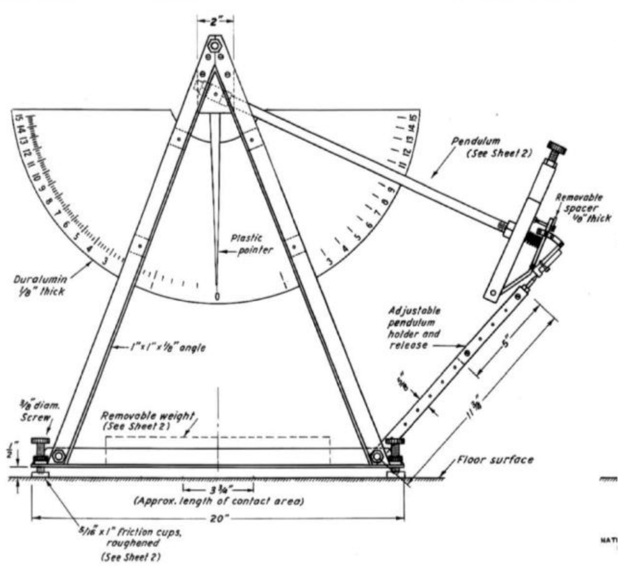

Figure 4 – The Sigler.
Source: Chang et al. 2001

Variable Incidence Tribometer: Also known as the English XL, it is an inclined strut slipmeter driven by a pneumatic cylinder. Manipulation of the impact angle allows calculation of a COF. It is a highly portable device and generally used for ensuring safe floor COF in the workplace.

Figure 5 – The Variable Incidence Tribometer (VIT), more commonly known as the English XL.
Source: http://www.englishxl.com/xl.html

Chapter 3

DESIGN AND VALIDATION:

Static tester

3.1 Objective

For initial sensor validation, the main objective was to design and build a device evaluating functionality of the slip sensor in horizontal and inclined positions. Functionality was determined by the ability to identify slip events based on a comparison of measured and predicted acceleration data. Large differences between the two indicate the onset or ending of a slip event.

3.2 Goals

Various design goals dictated the final concept. First and foremost, the device must cause high acceleration transients. Greater acceleration transients will result in more noticeable spikes in acceleration traces that will aid the sensor in identifying the bounds of slip events. The values of the measurements may also indicate needed adjustments in the processing algorithm.

The applied acceleration must have horizontal and inclined slope capability to ensure sensor effectiveness at different angles. More inclined situations would include a greater gravitational component in vertical acceleration and it is important that the sensor maintains functionality, especially since steeper floor inclines increase incidence of foot slippage. The variable nature of the values of acceleration based on degree of incline may show that a general threshold value will not suffice in the processing algorithm as it did for horizontal motion studies (McGorry et al., 2007).

To gather acceleration data at different friction coefficients that may be encountered, the floor surface itself must be changed during testing. Numerous floor surfaces expand the capabilities of the sensor and provide a larger database for construction of the slip identification algorithm. Changeable surfaces would allow for not only different surfaces, but different surface conditions as well. It is well known and has been for some time that friction coefficients vary greatly if the surface is contaminated. Once again, the variable nature of acceleration data based on the contact surface may indicate a threshold value of the difference between measured and predicted acceleration will not suffice.

If these goals are met, general sensor functionality can be assessed for a variety of surfaces, surface conditions, and angles. Based on its effectiveness, the processing algorithm may have to be adjusted and a simple threshold may not suffice for all applications.

3.3 Design

The ease of design and ability to achieve design goals led to the choice of a drag-sled test bed concept that has been extensively used to assess slipperiness (Chang, 2001). A simple concept, the drag-sled test bed utilizes a geared down motor with a cable to slowly pull a weight with sensor attached along a base surface (Figure 6), much like the HPS in Figure 2. Its simplicity allowed numerous improvements to better suit it to the goals of the experiment.

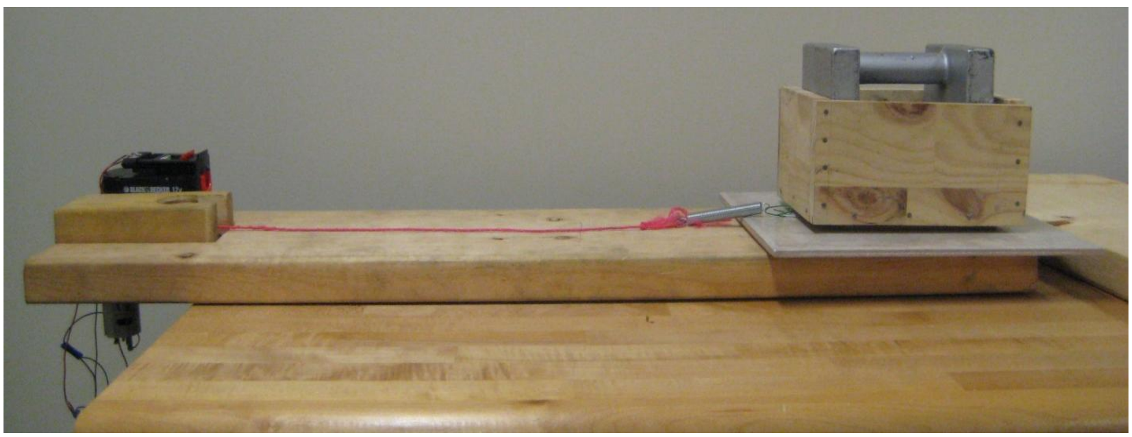

Figure 6 – Drag-sled static test bed.

Most notably, a stick-slip condition was induced in order to create acceleration transients that could be evaluated for slippage as well as maximize the number of measurements per run. Stick-slip was accomplished by adding a spring to the cable and by using a heavy deadweight. Rabinowicz (1958) suggests that a less stiff spring increases slip distance above the critical distance. The use of a heavier weight was necessary to produce large friction forces. As the motor drew in cable, the spring stretched without pulling the weight due to opposing static friction force (Figure 7). Eventually, spring displacement generated sufficient force to move the weight the distance drawn in by the motor, and then stop. This stick-slip condition repeated several times over the length of the base, providing numerous measurable acceleration spikes. Stick-slip can cause problematic effects, however, and Bowden (1945) deduced that the intermittent clutching and breaking away of the surfaces can trigger violent fluctuations in friction, surface temperature, and the area of contact.

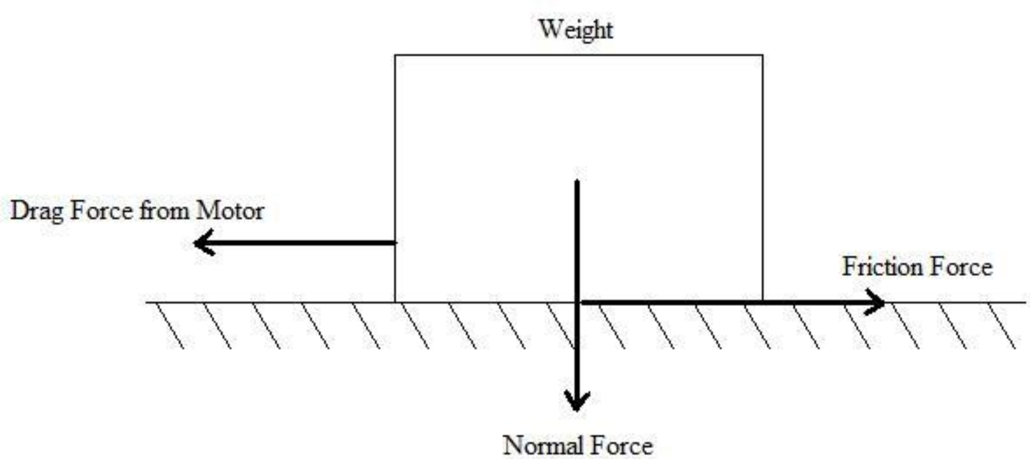

Figure 7 – Forces acting on the weight in drag-sled tester.

Surfaces and surface conditions could also be manipulated easily. Tile on top of the base permits surface interchangeability between different types of tiles and between wet or dry conditions. A friction coupon underneath a shoe holding the weight meant the rubbing surfaces were known and controlled. The shoe allowed changing the material of the friction coupon to either neolite or leather, which have been popular friction testing materials in the past (Bowden, 1945). Knowledge of the frictional characteristics during each set of measurements meant that data could be evaluated and compared to tabulated values in order to establish accelerations for each surface combination and the effect of different conditions.

Motor selection considered the power supply and available torque. While an AC motor could plug into any outlet, it only operates in one direction—pulling in the cable. On the other hand, a DC motor could operate in two directions—pulling in and drawing out—but requires either an adapter or battery pack for power. To aid portability, a DC motor powered by battery provided the necessary torque to move the weight. A double-pole, double-throw (DPDT) switch allowed bi-directional operation and an OFF position, during which further wiring meant the battery could be recharged without removing the electrical leads.

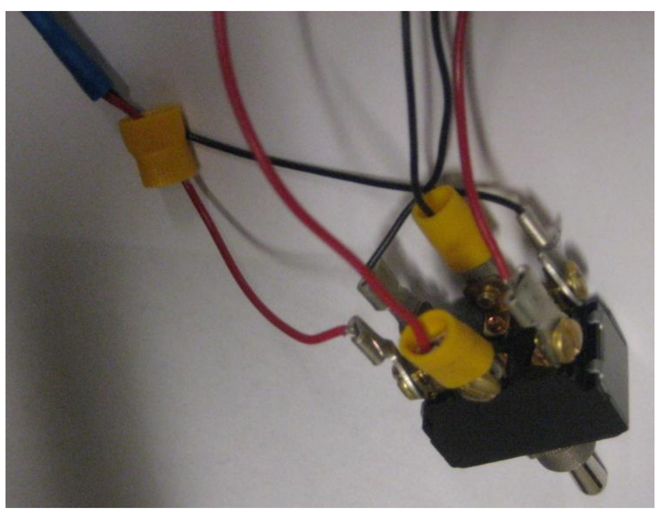

Figure 8 – DPDT Switch fully wired.

A DC motor with sufficient available torque to draw in a 25-pound weight was purchased from Servocity. It was rated for 34 lb overhung load and 55 in-lb torque, which easily accomplished the task of reeling in the dead weight using a 0.75-inch radius pulley. Due to the size and power of the motor, the vibration resulting from an intermittent load induced by stick-slip motion would have had negligible effect on its output.

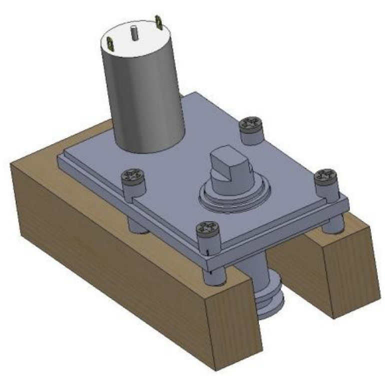

Figure 9 – DC Motor with gear box.

3.4 Validation

Experiments using the static tester yielded promising data. While in the horizontal position, stick-slip motion produced acceleration transients up to ± 2 m/s^2 with RMS sensor noise about ± 0.1 m/s^2 (Figure 10). The acceleration transients occur at the onset of slip and the moment when the mass ceases moving, and data matched nicely with these events.

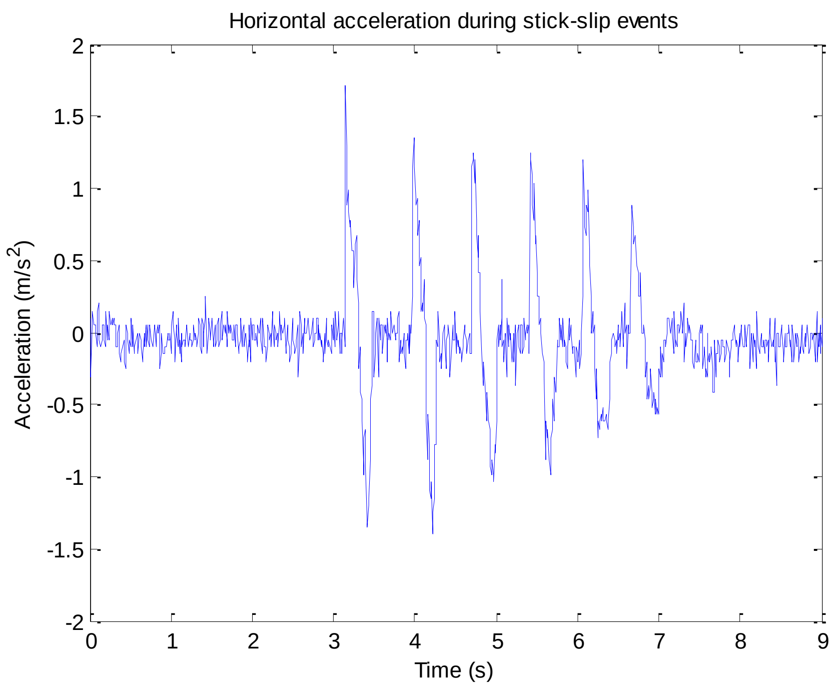

Figure 10 – Horizontal acceleration during stick-slip events at 0 degree incline. Note the clear direction changes during acceleration and deceleration of stick-slip.

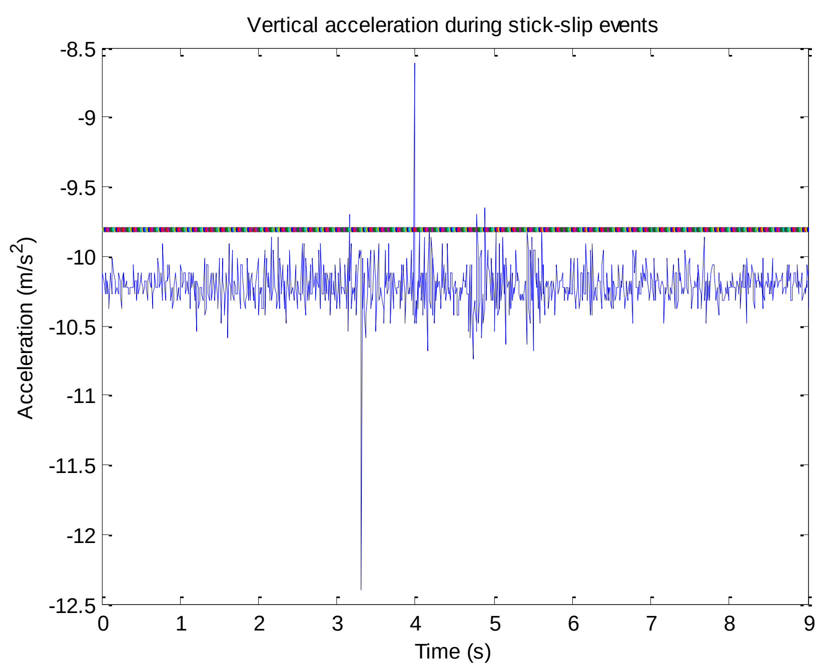

Figure 11 – Vertical acceleration during stick-slip events at 0 degree incline. Measurements slightly differ from the accepted value of gravity (9.8 m/s^2). Note that a slight oscillatory pattern exists during stick-slip motion, which indicates the sensor may not have been perfectly aligned vertically.

These results indicate that a threshold of 0.5 m/s^2 could be used to identify a slip condition. However, a simple threshold will not suffice due to higher mean accelerations produced at inclined positions. At a 9.5 degree angle from horizontal, static gravitational acceleration is 1.7 m/s^2, well above any potential threshold determined from horizontal data and would therefore cause a false positive indication of slip. The sensor algorithm must account for the large variations in static gravitational acceleration at different angles in order to minimize the possibility of falsely identifying slip.

3.5 Discussion

Due to the nature of the static tester, the higher accelerations associated with heel-strike could not be tested. This result was expected since the static tester cannot replicate the impact conditions at heel-strike. While horizontal stick-slip motion produced acceleration transients about ±0.2 g, McGorry et al. (2007) showed it is desirable to produce as much as 16g vertical deceleration and 6 g forward deceleration during the simulated heel strike of normal shod walking (25 degrees from vertical). The substantially larger transient accelerations at heel-strike explain why there is a greater incidence of slip associated with this contact condition. Also, it indicates that the sharp acceleration trace may better suit the sensor algorithm to easily identify a slip condition.

In terms of the design, the drag-sled tester could have been improved. The range of testable angles was small so the effect of static gravitational acceleration could not be fully explored. Inclines were achieved only by stacking solid objects to support one end without attachment to the main assembly. It was therefore not highly repeatable support despite the incline angle being maintained. Current results did determine that an ultimate threshold cannot be used to filter data but the extent to which angle affects gravitational acceleration can only be extrapolated.

The conditions of the base surface also did not permit highly repeatable acceleration data. While friction is inherently abrasive to any material, its effect on wood is greater than that on steel. The wooden base smoothed gradually, causing less abrupt stick-slip events and therefore lower acceleration transients over time. This served to exacerbate the problem of identifying slip events. Ideally, tiles placed on top of the wooden base would have acted as the friction interface, thereby decreasing the effect of wear.

In instances of stick-slip, it would be expected that the shorter stop time would decrease friction due to fewer asperity bonds that could be made between the rubbing surfaces. This was not always the case and a surprising phenomenon occurred when the wooden surface was lightly wetted with water – the friction increased. This has been noted in other literature and is attributed to sticktion, in which surface tension adhesion plays a significant role as long as both surfaces are properly wetted (Smith, 2002). Another hypothesis for a leather foot is that the increase in friction coefficient can be attributed to water-absorption softening, and therefore greater surface area for asperity bonding (Smith, 2002). Observation of this phenomenon will be important during further testing to ensure accurate slip resistance of the testing device.

It was observed that stick-slip events themselves vary considerably during a single test. The first event was the most pronounced and following events became smoother with incomplete stick until eventually the weight slid smoothly with no stick or velocity change at all. As described above, increasingly shorter stick time could have reduced asperity bonding and, as a result, the friction coefficient. Also, the stiffness of the system varied as the cable was drawn in. Greater system stiffness could have stifled stick-slip motion since the distance slid during slip dropped below the critical distance (Rabinowicz, 1958).

Chapter 4

DESIGN:

Dynamic tester

4.1 Objective

The initial tests performed by the drag-sled tester created isolated slip events that replicate conditions during stance phase. While certain acceleration spikes were measured, the acceleration trace was not sharp enough for the sensor to identify slippage. Additionally, slip events in general tend to occur at heel-strike, where impact produces higher accelerations. The dynamic tester will be designed to simulate conditions at heel-strike.

4.2 Goals

As a dynamic tester, the device must generate impacts between a base surface and a moving friction coupon. To replicate accelerations during normal walking heel-strike, the tester should be able to provide horizontal accelerations up to 6 g at impact. As such, the support structure must be able to withstand large resulting impact forces on the order of at least 100 pounds, using an estimate of a 15-pound shoe apparatus. Gill and O'Connor showed that normal, non-shod walking can produce acceleration at impact of 10.75 g (2003b) and McGorry et al. (2007) found accelerations of 17 g. It is likely then that acceleration transients produced by this action should be large enough for the sensor to effectively detect and identify slip events.

Similar to the static tester, the surface itself must be changed during testing to gather acceleration data at different friction coefficients. Due to the large forces at the point of heel-strike, the surface must be held firmly in place since any movement would affect the results of heel acceleration. An interchangeable friction coupon would allow for not only different surfaces, but different surface conditions as well. The inherent movement of the dynamic tester should eradicate potential asperity bonding effects and may well reduce the influence of sticktion.

Repeatability of the dynamic tester will be much more important than for the static tester. The higher incidence of slip at heel-strike is a primary concern for slip identification and accurate and repeatable acceleration measurements to formulate the processing algorithm are paramount. To ensure sensor functionality, the dynamic tester will see more test runs that provide a more refined algorithm in that regime. Also, the greater forces at impact are more likely to change the testing environment, such as causing imperfections in the floor or coupon material. The support structure of the dynamic tester itself will experience greater reaction forces and be more susceptible to failure mechanisms. The effect of surface wear experienced during the drag-sled testing demonstrated highly repeatable data may be difficult to produce. Materials with good wear characteristics should be chosen as the friction interface surfaces and should be monitored throughout testing.

If these goals are met, general sensor functionality can be assessed for a variety of surfaces, surface conditions, and impact conditions. Based on its effectiveness, the processing algorithm may have to be adjusted to better identify slip events at heel-strike.

4.3 Design

Due to its effectiveness and its relatively easy design, an English XL friction tester was chosen as the concept for the dynamic tester (Figure 12). The English XL tester utilizes the repeatable force of a pneumatic cylinder to evaluate friction coefficients by applying the force at variable angles (Figure 5). As a dynamic tester, the IMU mounted to the piston arm will measure acceleration during both non-slip and slip events dictated by the angle of contact.

Figure 12 – SolidWorks model of proposed dynamic tester design. Note a comprehensive Bill of Materials is in the APPENDIX A.

For the desired high impact accelerations, the support structure must be able to withstand large resulting impact forces and must therefore be scaled up from the English XL accordingly. If 6 g is required for an apparatus weighing about 15 lbs. (2 lb. cylinder rod, 0.5 lb. clevis, 0.5 lb. IMU, and a conservative estimate of 10 lb. shoe), the approximate force at impact is 100 lbs.

Since the primary feature of the English XL tester is its pneumatic cylinder, the support structure was constructed around its dimensions and characteristics. The UKF requires input of prior acceleration values to assess the difference in predicted and measured accelerations so a longer stroke length was desirable.

Single acting pneumatic cylinders contain a spring to retract the piston (Figure 13) and are actuated by compressed-air. However, the stroke length tends to be rather short for bore sizes that can withstand the large forces present in this application. Stroke lengths up to three inches may not give enough time to measure heel-strike accelerations compared to pre-strike conditions. To ensure proper function of the UKF, a longer stroke length was chosen (8 inches) which could only be supported by a double acting cylinder (Figure 14).

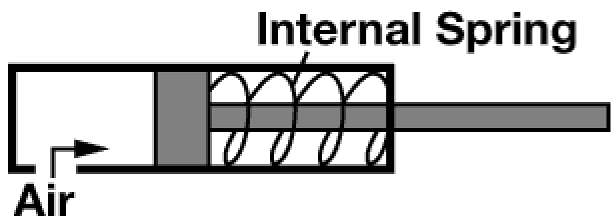

Figure 13 – Section view of a single-acting compressed-air cylinder.
Source: McMaster-Carr

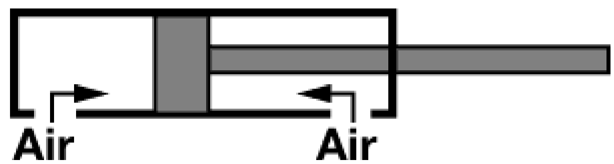

Figure 14 – Section view of a double-acting compressed-air cylinder.
Source: McMaster-Carr

The overall length of the chosen cylinder dictated the sizing requirements of the support structure. Previous experience prompted the selection of The Industrial Erector Set ® from 80/20 due to its reliability, strength, and ease of using pre-fabricated structural sets. The slotted supports available in the T-series, used in many linear motion applications, allow easy construction of the structure with minimal machining and tooling. Though the test structure is a scale up of the English XL tester, certain modifications to the support system and joints were made due to the greater forces produced. The pivot, stabilizing mechanism, and impact surface were of particular concern.

Large forces produced from the impact are translated to the pivot joint, which can be a weak point. The T-series includes high strength 90-degree pivot bracket assemblies (Figure 15) that will support the impact loads and provide the necessary rotation for testing at various impact angles.

Figure 15 – 90-degree pivot bracket assembly attached to 1515 T-series aluminum support beams.

To stabilize the support structure and keep it secure on the ground, the impact-side of the structure was extended compared to the English XL tester. This will allow the addition of dead weight that can effectively counteract the forces at the pivot joint and maintain structure ground contact. Any instance of lift off during impact will affect the acceleration measurements. Another stabilizing technique may be, depending on availability, that the front ends of the structure are bolted into the ground surface.

Due to the large forces, the friction surface itself is likely to slide if not properly held in place. Since the surface will change throughout testing and there is no base material other than the ground, forms of gluing or adhesion will not suffice as a primary method of stabilizing the surface. At the same time, any clearance from the ground may cause fracture of the friction surface, especially since many of them are brittle ceramic tiles. A gate in front of the friction surface with a light epoxy bead where there is contact with the support structure should be enough to impede its movement. Use of a position floor lock available in the T-series catalog was deemed unnecessary.

Actuation of a double acting pneumatic cylinder can be somewhat complicated. Simple calculations for a 2-inch bore indicate that for the desired impact force (100 pounds) only about 33 psi is required. Compressed-air lines in laboratories generally operate at over 100 psi. Additionally, the maximum force rating (290 lbs) for the cylinder suggests a maximum of 100 psi. Therefore, a regulator for compressed-air and its nozzle connector counterpart will be necessary for achieving desired impact forces and for the safety of the cylinder.

Since there will be only one drive force, the cylinder air feed requires a directional control valve. McMaster offers numerous valve options for two-pressure-output (four way) designs and a hand-operated lever air control valve was selected based on application and cost. Ports are 1/4-inch NPT female so piping and connections will be compatible with the chosen cylinder ports.

Another modification will be the addition of a replaceable foot attached to the clevis on the piston arm. The foot will ideally replicate the shape of a human foot so that impact area is similar and acceleration measurements will be as applicable to human locomotion as possible. Since it will be replaced at the clevis, the sensor can measure the effects of different materials, conditions, and even impact areas associated with different shapes. Further simulation of human heel-strike may require a torsional spring attachment to mimic the rotation of a heel during footfall, and thereby produce varying impact areas.

Chapter 5

CONCLUSIONS

5.1 Static tester

Static tests results were promising. They demonstrated the ability of the UKF to distinguish slip events even at low impact accelerations associated with isolated sliding. Data indicated that a threshold cannot be set to identify slip events since the acceleration values vary significantly with incline angle and a different method must be utilized in the sensing algorithm.

The static tester itself should be improved to make testing of multiple angles available. Unconnected support should not be used as a final evaluation of accelerations at different angles but rather an addition to the drag-sled design must be made.

In order to improve the reliability of the static tester, it is advised to use tiles attached to the base rather than the base itself. Wood has been observed to smooth after multiple test runs, leading to varying friction coefficients. It has also been observed that wood may absorb contaminant film causing sticktion, which may increase rather than reduce friction coefficient.

5.2 Dynamic tester

Results from the static tester indicated that more prominent acceleration traces should create conditions where a simple threshold suffices in the processing algorithm. The construction of the modified English XL dynamic tester should produce acceleration transients sharp enough for the Kalman filter to distinguish slip events at any impact angle, but it is currently still unknown since dynamic test runs have not yet been completed. Data may show that a complicated processing algorithm is still necessary.

Since the eventual purpose of the proposed sensor is to identify slip in robot feet, the processing time will be a prominent factor in its adoption. A more complex algorithm will take longer to distinguish normal movement and slip events and, when a robot has only a split second to adjust its balance before an impending fall, time is of the essence.

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APPENDIX A

BILL OF MATERIALS

Static tester

ITEM	SPECS	VENDOR
MOTOR	12 V DC 100 mA (no load) 55 in lb torque 34 lb overhung load 23 RPM 0.5” output shaft	Servocity.com
DOUBLE SWITCH	Cole Hersee DPDT On, off, on 6 screws	Instrument room
WIRING	20 AWG	Instrument room
PULLEY	0.75-inch radius	
CABLE	String	
SPRING type 1	15.88mm wide 82.55mm long including ends 1.83mm wire thickness Safe working load: 4.8lbs	Instrument room
SPRING type 2	11.11mm x 88.90mm x 1.20mm Safe working load: 2.1lbs	Instrument room
SPRING ATTACHMENT	‘S’ connectors	Instrument room
DEADWEIGHT	25 lbs	Instrument room
FRICTION COUPON	neoprene	
RUBBING TRACK	12” x 12” Tile	Lowe’s
BASE	Wood 8” wide 40” long	Lowe’s
SHOE	Wood and nails	Instrument room

Dynamic tester

ITEM	DESCRIPTION	VENDOR	ITEM #	#
CYLINDER	Stainless Steel Double-acting Pivot-Mount Compressed-air cylinder	McMaster	6498K482	1
TRUNION MOUNT	Zinc-Plated Steel Pivot Bracket	McMaster	6498K564	1
CLEVIS ATTACHMENT	Zinc-Plated Steel Rod Clevis with Pin	McMaster	6498K554	1
SUPPORT BEAM	1515 T-Series 6105-T5 Aluminum 40” 25” 15”	80/20	1515	 2 2 1
STANDARD END FASTENERS	6105-T5 Aluminum	80/20	3682	2
4 HOLE INSIDE CORNER BRACKET	6105-T5 Aluminum	80/20	4301	2
90 DEGREE PIVOT BRACKET	6105-T5 Aluminum	80/20	Right 4337 Left 4333	2 2
0 DEGREE LIVING NUB	6105-T5 Aluminum	80/20	4381	2
TILE		Lowe’s		
DOUBLE T-NUT	¼” – 20 Black Zinc-Plated Steel	80/20	3356	4
TRIPLE T-NUT	¼” – 20 Black Zinc-Plated Steel	80/20	3358	4
STANDARD T-NUT	¼” – 20 Stainless Steel	80/20	3605	5
REGULATOR	Lever control	McMaster	4158K72	1
DIRECTIONAL CONTROL VALVE	¼” NPT ports 2 output (4 way) Hand-operated lever	McMaster	3368K44	1
NOZZLE CONNECTION	Quick-Disconnect	McMaster	5012K93	1
TUBING	Opaque Black Nylon	McMaster	5097T411	10 ft.

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Mainstream Engineering Corp., *Intern* Melbourne, FL Summer 2009
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Summer abroad in Australia
Genesis Engineers, Inc., *Intern* Plymouth Meeting, PA Summer 2006
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