ABSTRACT

AN INVESTIGATION OF MEASURING ENERGY AND POWER DURING WALKING ON SLOPES USING FOOT MOUNTED INERTIAL MAGNETIC SENSORS

by Hawkar Ali Oagaz

To more fully immerse users in virtual environments, the use of a natural walking locomotion interface has been shown to be superior in simulating natural feelings. In such systems, simulating sloped areas is more difficult than level ground. In the physical world, navigation over slope requires more energy than level terrain. In the absence of physical slope in the laboratory, this question arises; how can we simulate slopes in a manner that make users consume more energy to go up and down slope? For solving this problem, we propose an approach that uses a small foot-mounted inertial/magnetic sensors. A “Self-Contained Inertial Position Tracking” (SCIPT) system that processes sensor data produces estimates of position, velocity and acceleration of the feet. With these measurements, “total energy” consumed by the user is calculated. The relationship between “total energy need” to ascend or descend any slopes and instantaneous measures of “total energy consumed” by the user controls how quickly the user is able to navigate virtual slopes. By manipulating this relationship we can force the user to walk in a particular way. For steep inclines, the user has to walk faster, further, and/or lift up their feet higher to match the effort required on real slopes. Our data have shown the kinetic energy is calculated successfully. The kinetic energy estimates enabled measurement of increased effort associated with walking faster or further. Potential energy estimates were inconsistent due to the inability of the SCIPT systems to accurately estimate step height. Thus, the greater effort associated with higher steps could not be measured.
AN INVESTIGATION OF MEASURING ENERGY AND POWER DURING WALKING ON SLOPES USING FOOT MOUNTED INERTIAL MAGNETIC SENSORS

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Dedication

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1 Introduction

Virtual reality can create immersive environments that provide us with the opportunity to experience unusual or hazardous situations that are not common in everyday life. Virtual environment simulations often include situations that are life threatening or too expensive to create in the real world, such as training firefighters with unfamiliar buildings prior to their task [1]. The goal of immersive virtual environments is to produce experiences that are as close as possible to the real life [2]. Using some physical devices in virtual reality could increase the feeling of fully immersed in VR [3]. However, physical devices might provide physical feelings or track some human physical activities that make user more feel like the real life.

Previous research has shown that the use of natural walking as a locomotion interface can increase the sense of being “present” in the virtual simulation [4-6]. Allowing users to explore virtual worlds that are greater in size than the physical tracking area, and providing a way to support natural walking have been two main challenges for VE researchers. Techniques such as redirected walking [7] and resetting [8] have been successful in enabling users to explore virtual worlds that are unlimited in size. However, in order to simulate natural walking with greater fidelity, more research still needs to be done. Simulating sloped ground for users that are walking on a level surface is a challenge that has not been met. In the physical world, users have to expend a greater amount of energy to walk uphill. Simulating uneven surfaces in an immersive virtual environment (IVE) that supports natural walking is difficult because there is no physical resistance that the user can feel.

In this thesis, we explore a simple, low-cost, low-power approach to simulating slope in virtual environment systems that support natural walking. The approach is based on the use of small foot-mounted inertial/magnetic measurement units (IMMUs) to measure the amount of energy and power output of the user during walking. It was intended that users with an increased energy/power output are would be able to move “uphill” faster. On the other hand, users that did not increase their energy/power output upon encountering a simulated slope would see their forward progress slowed within the virtual world.

Nardi, Newcombe and Shipley [9] showed that how slope helps humans remain oriented changes behavior. Often, elevation and type of terrain are significant factors in path planning. The goal of this thesis is to produce user behaviors in a virtual environment that closely match behaviors that
occur in the physical world when humans are required to navigate sloped terrain. The contribution of this thesis includes the following:

- Development of a method for measuring user work and power output during walking
- Development of a technique for scaling translational movement in a virtual world based on the energy and power output of the user
- Achieve previous two goals with low-price and low-power sensors.

1.1 Results

Total mechanical energy consists of kinetic energy and potential energy. Kinetic energy depends on the velocity of the object which indicates how fast the object is moving. While potential energy depends on the vertical position of the object which indicates how high the object is from the ground. Our data have shown that we can consistently measure velocity and therefore kinetic energy measurement is also consistent. However, due to inconsistencies in calculating vertical position using self-contained inertial position tracking (SCIP), the potential energy cannot be calculated consistently.

1.2 Organization of the Thesis

This thesis is divided into five chapters. Chapter one is an introduction of the thesis and our goal. In chapter two, we talk about a background and work that is related to this thesis. We also present a method for calculating work. In addition, we present how slope changes human behavior. In chapter three, we describe our approach in detail and present the sensor devices utilized in this research. Chapter four describes user study experiments and explains how they were conducted. In the last chapter, we present our results and the conclusions of the thesis.
2 Background

The background for this thesis work is divided into three main areas. The first area pertains to how slopes can change human behavior during walking and how important a factor slope can be in our daily lives. Since our approach is to use the physical energy/power generated by the user to control user’s walking speed of movement on virtual slopes, the second area of background pertains to what measurements and calculations are necessary to calculate work/total energy and power. Previous work related to simulating slope in virtual environments is the last area of background to be discussed.

2.1 How slope changes behavior

The physical environment around us rarely is completely flat. Inclines appear due to the presence of hills, valleys, and other kind of slopes. In addition, man-made structures such as ramps, stairs, ladders and elevators require three-dimensional navigation. As we encounter inclines in our daily lives, these slopes can determine our path from one point to another as well as help us to remain reoriented.

Experiments have shown that rats can use slope to remain oriented when searching for food. They can estimate inclination to determine the quickest path to reach a destination. In an experiment done by Miniaci, Scotto and Bures [10], four feeders are located in different corners of an arena. The rats were placed in the center of the arena, equidistance from the feeders. The laboratory arena contained no visual stimuli that rats could possibly use. Slope was detected only through kinesthetic and vestibular queues. When the arena was tilted 10%, the rats could successfully find their goal 90% of the time on their first attempt. When the tilt was present, the rats found their goal 83% of the time when the same experiment was conducted in darkness. In contrast, rats performed in a random manner when the inclination was removed. These results indicate that slope can be used by rats to determine the direction towards a goal.

As discussed above, animals can successfully use slope to determine direction in a featureless room. To examine similar human behaviors, Nardi, Newcombe and Shipley utilized a featureless room that could be tilted 5 degrees [9]. The goal assigned to participants was to find a reward after being spun in a swivel chair while blind folded. The participants were shown the location of the award prior to being spun. In scenarios in which the room was not tilted, participants could not
find the reward with any better than random success. When the room was tilted by 5°, they could find their direction to the goal reliably, the mean of male performance success was 78.8% ± 16.77 while the mean of female performance success was 42.5% ± 32.55. These results indicated that the participants used cues that come with sloped ground to orient themselves. These cues included joint angles, muscular effort, and visual cues of the angles that are made where the walls and tilted floor intersected (the angle between wall and uphill is a little bit obtuse whereas it’s slightly acute on downhill side).

Slope has a significant role in the navigation in the natural environments. Whitaker and Cuqlock-Knopp conducted interviews with a group of 16 civilian orienteers and military scouts [11]. The goal of the research was to determine what kind of navigation skills are required to navigate in off-road environments. The research showed that besides visual cues and problem-solving strategies, the participants used the slope of terrain as a primary cue for remaining oriented. Reducing physical expenses and maximizing the effect of selected route are two basics of navigation decision making. Thus, route selection is heavily influence by how easily a given terrain can be traveled on. Seiler [12] who has done a research on the performance of elite orienteers, stated that “orienteers evaluate a longer and easier route for a shorter, but steeper one”. Also, one of the novice orienteers mentioned that he asked himself “Do I run longer around the road or take a more direct route, but with more elevation change?” Another one said “You can climb 1 ft. in elevation as quickly as you can run 10 ft. horizontally [11].”

2.2 Calculating work

In physics, work is the output of a force acting upon a body that causes a displacement of the body. Work is defined by [13]

\[ W = \vec{F}d \]

(2.1)

where \( \vec{F} \) is the component of force acting in the direction of movement and \( d \) is the displacement of the object. Work is a scalar quantity that can be either positive or negative. Pushing a body forward is positive work while the work done by gravity on the object being lifted up is negative. Work is equal to zero if the force does not move the object that it is applied to. The unit of work is the result of multiplication of the unit of force by the unit of distance. In the International System of Units (SI), the unit of force is Newton (Kg.m/s²) and meter (m) is the distance unit. In the SI
system, the unit of work is the *Joule*. When 1 Newton of force is applied to an object and displaces it by 1 meter, one *Joule* of work is produced [13].

### 2.2.1 Work with constant force

Forces can either push or pull. Force is a vector quantity (has a direction and magnitude) [13]. If the direction of the force is the same as the direction of displacement, the force does positive work. If the direction of the force is in the opposite direction of displacement, the force does negative work. Work is bigger if the force or the displacement is greater. Constant forces are forces that are applied to a body with the same magnitude and direction throughout the process.

If a force doesn’t push (or pull) an object the same direction as its displacement, the force can be divided into two vectors. For example, a force that pushes at angle \( \theta \) relative to the direction of movement is divided into component parts, that will consist of component vectors \( \vec{F}_x \) and \( \vec{F}_y \).

\[
\vec{F}_x = \vec{F} \cos \theta \tag{2.2}
\]

\[
\vec{F}_y = \vec{F} \sin \theta \tag{2.3}
\]

If the displacement is only in the horizontal direction, the work carried out by the force \( \vec{F} \) will be equal to

\[
W = \vec{F}_x (x_2 - x_1) \tag{2.4}
\]

Where \( x_2 - x_1 \) is equal to the displacement.

By Newton’s second law: “The acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the acceleration, and is proportional to the mass of the object.” Thus, the total \( F \) on object \( O \) will be:

\[
\sum \vec{F}_i = m\vec{a} \tag{2.5}
\]
2.2.2 Work with non-constant force

The previous work calculations are based upon a constant force. However, forces often vary during movement. An example for this kind of force is the stretching of a spring. The greater the stretch, the larger the force needed to extend it the same distance. Figure 2.4 depicts a function that describes how the required force changes as the position of the object is changed. At position $x_1$, force $F_{x_1}$ is needed to move the object to the next position. As the object is moved towards position $x_2$, the positive slope of the function indicates that required force increases when displacing the object for the same distance. We can calculate work with non-constant force as follows [13]:

- Divide total displacement to small segments.
  \[
  \Delta x_a, \Delta x_b, \Delta x_c, \ldots
  \]  
  \(2.6\)

- Find work for each segment individually
  \[
  \bar{F}_{a} \Delta x_a, \bar{F}_{b} \Delta x_b, \bar{F}_{c} \Delta x_c, \ldots
  \]  
  \(2.7\)

- Sum together the work required for each of the segments.
  \[
  W = \bar{F}_{a} \Delta x_a + \bar{F}_{b} \Delta x_b + \bar{F}_{c} \Delta x_c + \ldots
  \]  
  \(2.8\)

In the limit as the width of the segments goes to zero, work is equal to the integral

\[
W = \int_{x_1}^{x_2} \bar{F}_x \, dx
\]

\(2.9\)

2.2.3 Power

The definition of work does not involve time. In other words, moving a given mass a specified distance will result in the same amount of work regardless of how long it takes. Power conveys the rate at which the work is done [13]. For instance, if someone moves a box with a 100 N constant force a distance of 1m, the work will be $(100 \text{ N}) (1\text{ m}) = 100 \text{ J}$. However, we don’t know if the box
movement was accomplished in 1 second, 1 minute or 1 hour. By involving time, we can know how fast the work was done. Intuitively, power should need to be increased in order to accomplish the same amount of work in a shorter time period. Average power is the quality of work done during an interval of time. Thus, it is defined as:

$$P_{av} = \frac{\Delta W}{\Delta t}$$  \hspace{1cm} (2.10)

We can calculate instantaneous power as $\Delta t$ approaches zero

$$P = \lim_{\Delta t \to 0} \left( \frac{\Delta W}{\Delta t} \right) = \frac{dW}{dt}$$  \hspace{1cm} (2.11)

Power is a scalar quantity like work and the unit of power is Watt (W) in the SI unit system. One Watt is equal to 1 Joule per second: $1 \text{ W} = 1 \text{ J/s}$. In mechanics, the power could be defined in terms of force and velocity:

$$P = \vec{F} \cdot \vec{v}$$  \hspace{1cm} (2.12)

### 2.2.4 Kinetic Energy

Kinetic energy is the energy that is needed to move an object from point A to point B regardless of its direction [13]. It depends only on the velocity and mass of the object. For example, if a car is moved to north at 10m/s or to east with the same velocity, the same kinetic energy is required. Similar to work and power, kinetic energy is a scalar quantity. Since the direction has no role in the equation, the kinetic energy is always positive if there is a displacement. It’s zero when the object is not moved. The equation of kinetic energy is defined as:

$$K = \frac{1}{2}mv^2$$  \hspace{1cm} (2.13)

Figure 2.6a and figure 2.6b and figure 2.6c depict some cases of changing kinetic energy, according to its equation depending on the velocity and mass. As shown in figure 2.6a, since the mass and velocity are the same, the kinetic energy is the same. Notice in equation 2.13, the velocity is squared which makes the value to be positive in all cases, therefore, the output is always positive. Figure 2.6b shows that when we have the same speed but twice the mass, the kinetic energy will be doubled. Figure 2.6c illustrates a situation when there is the same mass but twice the speed then it results to four times the kinetic energy.
2.2.5 Potential Energy

In the previous section we defined kinetic energy as the motion of an object regardless of its direction. Here we are defining potential energy which is associated to the object’s position rather than its motion [3]. For example, when a diver jumps on the diving board and quickly descends to the water, you might ask where this energy comes from. The answer is gravity. The gravity still pulls him down and because the board is pushing him up he doesn’t fall. While jumping, the energy is transformed from one form (potential energy) to another (kinetic energy). Thus, we can see how the position of the object is associated with energy. The sum of potential energy and kinetic energy is called total mechanical energy. If an object moves (upward or downward), the energy exerted by this object depends on its location and weight. As shown in figure 2.7. This energy is called the gravitational potential energy, $U_{grav}$:

$$U_{grav} = mgy$$  \hspace{1cm} (2.14)

Where $m$ is mass, $g$ is gravity and $y$ is vertical replacement.

To see how the gravitational potential energy could be useful, figure 2.8 illustrates the condition. If a gravitational force is acting on an object and the object is moving upward or downward, then the total work done on that object is the change in kinetic energy or the total of kinetic energy and gravitational potential energy which is total mechanical energy. Thus, Work = $K + U_{grave}$:

$$Work = \frac{1}{2}mv^2 + mgy$$  \hspace{1cm} (2.15)

Figure 2.6a: Kinetic energy, same mass, different direction [13]

Figure 2.6b: Kinetic energy, different mass, same speed [13]

Figure 2.6c: Kinetic energy, same mass, different speed [13]

Figure 2.7: Gravitational potential energy [13]
Figure 2.8 illustrates the principle of *Energy Conservation*. This principle states that the total energy quantity has the same value over the time. This happens when gravity is the only force that acts upon the object. A practical example of conserved quantity is when we throw a ball in the air while neglecting air resistance (gravity is the only force). When the ball goes up, its kinetic energy is decreased because it converted to potential energy, but when it goes down the opposite happens. This conversion of potential energy to kinetic energy makes the ball move faster on its way down. The total mechanical energy remains constant all the way through.

### 2.2.6 Total Energy

Total energy or mechanical total energy is the summation of potential energy and kinetic energy as shown in equation 2.15 [13]. Total energy represents both how fast the object is moving because it includes kinetic energy in the calculation. Also, it represents what the height of the object is because it includes potential energy in the calculation. Adding to that, total energy is equal to work done by the object to move from one point to another one as shown in section 2.2.5. In this thesis total energy, total mechanical energy, work and energy will be used interchangeably.

### 2.3 Previous Slope Simulation

In the following, section we will review related work that has been done to simulate slope in virtual environments. This background work is classified according to the general approaches that have been used. The categories that will be covered through this section are treadmills, foot pads, motor-pulley mechanism and other techniques category that contains some approaches that are different the rest of other approaches.
2.3.1 Treadmills

Treadmills have been successful in simulating natural walking in virtual reality. They have been shown to allow the goal of the limitless walking to be reached. Iwata et al. [14-15] describe the Torus treadmill. The Torus treadmill is an attempt to offer natural omnidirectional waking to users. It is composed of 12 torus-shaped surface treadmills that are connected to each other side-by-side. The 12 treadmills circulate in a direction that is perpendicular to the movement of the driven belt surfaces. The Driven surfaces and treadmills move opposite the movement direction of the walker in order to maintain the walker in position; canceling the motion of each step. This process generates an infinite walking area and makes omnidirectional waking possible. The maximum speed of circulating treadmills and the surface of each treadmill is 1.2m/s. while the active area for walking is 1m x 1m with a step length limitation of 30cm. These limitations force the walker to walk slower than natural walking and running is not possible. However, the measured pressure of feet and walking trajectories resemble natural walking. The Torus Treadmill potentially can simulate walking on the uneven area with some restrictions. For instance, the users cannot make rapid changes in direction.

The Omni-directional treadmill (ODT) is another treadmill approach that was studied by Darken [16]. The ODT is a large complex system that consists of two treadmills that are placed perpendicular one on another. Each treadmill belt consists of approximately 3400 separate roller that have been woven into a mechanical fabric. Servo motors are used to control user’s motions.
The ODT’s dimensions are 2.21m x 2.01m with a 1.3m x 1.3m active surface area. With the user in the center, she/he is surrounded by 0.635m active surface in each direction. Because of mechanical parts that it consists of, operation of the ODT produces noise in the 85dB range. A tracking arm is attached to the user to track location and maintain them in the active area. The user cannot exceed a velocity of 4.5mph (2m/sec) relative to the treadmill. If a user starts walking rapidly after being stationary, the ODT is limited in how quickly it can respond to keep the user in the active area. Lag in the process makes running on the ODT impossible. Walking on the ODT is somewhat unnatural and unbalanced compared to natural walking and can result in stumbles [16].

In some cases, a forward stumble can occur when the user stops quickly, because the treads cannot stop as quickly as the user. Quick turns can also cause users to get off balance and can be difficult to execute on the ODT. Turning in place is also not easy because the system always brings the user back to the center with each step the user has taken. Based on these observations the researchers suggested that “Skill level plays too important a role in determining the usability of the system”. However, the ODT works well during walking and jogging with a steady velocity and users can walk infinitely when using the ODT.
In general, the treadmill approach has two major problems: controlling the speed of the treadmill belt and the direction of walking. The ATLAS: ATR Locomotion Interface for Active Self Motion [17, 18] is another device designed to simulate locomotion using a treadmill approach. ATLAS provides a solution for the first problem by estimating the walking speed using visual motion techniques to control the belt speed. Consequently, ATLAS reaches the goal of not requiring users to relearn how to walk and of getting rid of obstructive sensors. ATLAS uses a motor-driven treadmill with belt dimensions of 1.45m x 0.55m and a three axis motion platform that can tilt and maintain user walking position during movement in any direction. For a user to walk naturally on a treadmill, the treadmill has to operate in the same speed in the opposite direction of the user’s walking. Due to mechanical delay, this can be hard to control [18]. Thus, the system has to adjust the speed according to the user’s position and his walking speed. To detect a user’s position and his walking speed, ATLAS uses a camera and three magnetic position sensors (IR reflectors). One sensor on the waist and two sensors on walker’s toes, one for each foot. The user’s position is estimated based on the toe position. This speed estimation method uses the duration of the gait stance phase on the treadmill to detect user’s walking speed. There is 0.2s delay for the system to react of any speed change (0.1 by ATLAS to detect motion changes and 0.1s for the belt to react), therefore, the system uses primary feed forwards to cancel error that is generated by the speed estimation unit. Walking on ATLAS is not exactly the same as on the ground. On ATLAS, strides are a little shorter and duration of the swing phase is longer with a shorter stance phase [18]. Experiments showed that some participants couldn’t walk on ATLAS because of the lack of constant speed as participants’ desired, instead they just reacted to the movement of the belt. Also, because of the delay time (0.2s) the walkers couldn’t stop when/where they desired. This required users to learn how to reduce their speed gradually before stopping.

Figure 2.11: ATLAS [17]
2.3.2 Foot pads

Foot pads are designed to simulate uneven walking areas such as stairs. The GaitMaster, described by Iwata et al. [6], simulates the sensation of walking on uneven surfaces. The device consists of two motion platforms that are mounted on a turntable that can go up and down. Platforms move horizontally opposite of walking direction to cancel steps and move vertically to simulate uneven surfaces. All this happens while the position of user is maintained. The turntable can rotate in any direction to provide omnidirectional walking. Physical configuration is described as:

When the user stands on the top of the motion platforms, the platforms track user’s horizontal motion by moving forward and backward in the opposite direction of walking to cancel user’s feet movement. Meanwhile, platforms go up and down to cancel user’s vertical movement. Turntable’s motion controls user’s orientation. Rotating in yaw axis to simulate horizontal motions. Rotating around the roll axis and/or pitch axis to simulate incline in virtual environment [6].

With this process, the GaitMaster can simulate infinite stairs such as an escalator. To keep the user on the stairs, GaitMaster checks the position of the downward foot after it has been lifted up and moves the motion platform underneath it. The GaitMaster can rotate the turntable depending on direction of the feet. Vertical walking is limited to steps that are less than 20cm and a maximum horizontal walking speed is 1.5m/s.

Another approach that uses the foot pad technique is the CircularFloor [4]. This locomotion system consists of four holonomic omnidirectional carrier vehicles with dimensions of 568mm x 568mm x 92mm and a weight of 16.2kg. Each tile can carry 80kg with a maximum speed of 1.2m/s. All are connected to a PC via wireless. With position sensors on the feet the system moves tiles in the opposite direction of the walking which cancels the motion of steps. Since tiles have cyclic movement, they could cancel motion of any arbitrary direction. This process gives the user freedom to change his/her direction. However, due to limited speed, the walking is not quite
natural. Users can walk with maximum speed of 0.33m/s in alternating mode (tiles are attached next to each other) and unidirectional mode (titles are attached with half of them touching each other to make a diagonal pathway) and with a velocity of 0.21m/s in crossed circulation mode (the user is circulating around a certain place).

![String Walker](image)

**Figure 2.13: CircularFloor [4]**

### 2.3.3 Motor-pulley mechanism

String walker is a device that uses a motor-pulley technique to implement a locomotion interface for virtual environments [5]. Eight strings are used to attach two special shoes (four for each shoe) to a turntable where they are actuated by a motor-pulley machine. The motor pulls strings in the opposite direction of walking during the stance phase of gait (it doesn’t pull while the foot is in swing phase) to cancel steps and keep the user in the center of the table. Strings are motor-driven by a turntable which is rotatable and can reorient depending on feet’s position. All four strings for each foot can be pulled in any direction which enables omnidirectional walking. With string walker, the user can walk in any direction with any gait type, forward, backward and side-walking. The string walker is easy to step up, except for the turntable which needs half a day and a space of 13ft x 20ft. The string walker is able to provide unlimited flat walking ground area in virtual space, however, it cannot simulate uneven areas.
2.3.4 Other techniques

Virtusphere uses a technique that is different from the approaches mentioned in previous sections [19]. Virtusphere is a device that simulates walking through the use of a sphere with a user walking within it. It uses a Head Mounted Display (HMD). Virtusphere can cope with the physical distance limitation. However, it is not capable of simulating slopes. Sphere inertia and walking on a curved surface can distract the user while walking in VE. This decreases natural walking feelings compared to normal walking. Also users have found walking fast and turning difficult [19].
The Virtuix Omni is an omnidirectional locomotion interface platform that enables user to walk and run in limitless space in virtual environments [20]. In addition to walking and running, the user can sit and strive in any direction. The Omni consists of a concave, low-friction dish shaped base, a support ring and safety harness, and low friction shoes. Users stand in the center of the dish and step to the outside of the dish when walking, or running. The concave platform is designed such that the feet slide back to the center of the dish following each step. Since little or no user effort in involved in bringing the foot back to the center of the dish, the manufacturer claims that the device better simulates natural walking than similar devices with a flat platform. The player can jump and rotate rapidly to face any direction. Presently, the focus to the Omni is to simulate
walking and running on a level surface. No attempts have been made to simulate sloped terrain. The Omni’s dimensions are 140cm x 139cm x 89cm.

### 2.4 Summary

In this chapter, we covered three sections in detail. In section 2.1 we presented how slope can impact human behavior. We mentioned two research work done on rats and humans [9, 10], both works reported how the reorientation and finding of goals were improved when the ground was tilted. In addition, we presented other research that done regarding navigation in natural settings during scouting and hiking activates [11, 12]. Since in our approach we are using energy and power as the main factors to change virtual speed, section 2.2 covered the physical descriptions and laws for calculating work, power, energy, kinetic energy and potential energy. Section 2.3 was illustrated the background and previous work in simulating slopes in virtual environments. We showed many different approaches that have been done in this area. We divided the approaches to four different categories. The categories that we went through were treadmills, foot pads, motor-pulley mechanism and other techniques that included the Virtusphere and Virtuix.
3 Approach

Ascending and descending slopes respectively requires greater and lesser amounts of effort relative to walking on level ground. In VE systems that support a natural walking locomotion interface, users physically walk only on level surfaces. Thus, it is not possible to simulate virtual slopes in a way that is completely faithful to that of the physical world. Instead, the approach adopted here will be to measure the total mechanical energy output of the user by means of foot mounted inertial/magnetic measurement units (IMMUs). The virtual walking speed with which a user goes up or down virtual slopes will be based on their total mechanical energy output relative their typical energy output on a level surface. When ascending a slope, users would only be able to maintain their virtual walking speed if they increase their energy output to a level that is equal to what would be necessary on a physical slope with the same incline. This increased energy output can be achieved in multiple ways including walking faster or lifting the feet higher. The chapter describes the sensors and calculations that will be used to determine the level of effort of the user.

3.1 Foot Mounted Inertial Magnetic Sensors

The 3DM-GX3-25 is an IMMUs sensor. It is based on microelectromechanical systems (MEMS) [21]. This sensor incorporates a three-axis linear accelerometer, three-axis magnetometer and a three-axis angular rate sensor that produces three dimensional measurements of linear acceleration, the local magnetic field, and the rotational rate of the sensor. The sensor has a data output rate of up to 1000Hz. Its dimensions are 44 mm x 24 mm x 11 mm with a weight of 18 grams. It can be connected to a computer via USB 2.0 or RS232 [22].

In this work, sensor data are output via USB 2.0 to a laptop computer (Dell Precision M4500, with Intel processor Core i7 CPU Q840 1.87GHz (8 CPUs)). A Self Contained Inertial Position Tracking (SCIPT) Software System processes the data and determines foot acceleration, velocity, orientation, and position [21]. The SCIPT-API sends position estimate to a renderer which is
connected to a Head Mounted Display (HMD). Both computer and renderer are located in a wearable backpack.

3.2 Self-Contained Inertial Position Tracking (SCIPT) System

All vector quantities output by the 3DM-GX3-25 are measured in a moving body coordinate frame. The SCIPT-API takes these vectors as input and transforms them to an Earth-fixed reference frame in order to estimate foot position, foot orientation and gait phase [21]. Acceleration sensors are an efficient approach to analyze and detect walking behaviors [23]. Velocity data are corrected using Zero Velocity Updates (ZVU) [21]. Foot velocity and position are calculated through trapezoidal integration of the corrected acceleration data [21, 24].

The acceleration vector that is obtained directly from the sensors contains errors due to measurement bias and drift. Theoretically the velocity vector could be attained from the acceleration vector through integration and then integrated to estimate position. However, due to systematic errors in acceleration measurement, position estimates obtained in this manner would be inaccurate and unusable. ZVU is an approach that has been used to reduce the position error growth by correcting the velocity [21]. The concept of ZVU is that human walking is cyclic, and when the foot is on the ground or in stance phase the velocity of the foot is known to be is zero. Because of the errors in measuring acceleration, the measured velocity will not be zero when the foot is in contact with the ground. The difference between measured velocity and actual velocity (known to be zero) can be used to correct velocity data from the previous swing phase [21]. Figure 3.2a and figure 3.2b illustrate velocity before and after applying the ZVU. Figure 3.2a shows how the velocity estimate drifts and thus measured velocity is not zero when the foot is on the ground. This error grows with time. Figure 3.2b shows the velocity after application of the ZVU correction. It is apparent that the velocity is zero when the foot is on the ground.
Estimation of Instantaneous Kinetic and Potential Energy of the Feet

Total mechanical energy is equal to the sum of kinetic and potential energy. In order to determine the total energy output during walking, the SCIPT system was modified to calculate instantaneous kinetic and potential energy.

Kinetic energy accounts for the speed of movement of the foot and ultimately its change in position. In order to account for the work associated with changes in position, instantaneous kinetic energy of the foot is calculated using foot velocity by

\[ \frac{1}{2} m (\vec{v} \cdot \vec{v}) \]  

where \( m \) is the mass of the foot and, can be assumed to be constant and equal to one and \( v \) is the velocity of the foot in meters per second.

Potential energy is used to account for the work against the force of gravity and is given by

\[ m (\vec{g} \cdot \vec{p}) \]  

where \( \vec{g} \) is the gravity vector and \( \vec{p} \) is the position of the foot. Again, the mass can assumed to be constant and equal to one. Gravitational acceleration is measured in meters per second per second and the gravity vector is given by

\[
\begin{bmatrix}
0 \\
0 \\
9.8
\end{bmatrix}
\]  

3.3 Estimation of Instantaneous Kinetic and Potential Energy of the Feet
Since the x and y components of the gravity vector, are equal to zero, the dot product can be simplified to a the scalar multiplication

\[ 9.8(p_z) \]  

(3.4)

Where \( p_z \) is the vertical component of the position vector for the foot and is expressed in meters. Combining equation (3.1) and (3.2) produces the instantaneous total mechanical energy of the foot

\[ \frac{1}{2} m(v^2) + m(g^2) \]  

(3.5)

For the purpose of determining relative energy output, this can be simplified to

\[ \frac{1}{2} (v^2) + (g^2) = \frac{1}{2} (v^2) + 9.8(p_z) \]  

(3.5)

### 3.4 Verification of Correctness of Kinetic and Potential Energy Calculations

Synthetic data were used to verify the correctness of the potential and kinetic energy calculations and their implementation. Sine curve was used to generate synthetic data that simulates foot velocity and foot height during the swing phase of the gait cycle. The goal was to show that increased velocities would result in increases in kinetic energy and that increases in foot height would result in greater potential energy output. Though, the synthetic data are not an exact representation of the real data or the exact shape of the real data, they demonstrate the validity of the approach of this thesis.

The circle represents movement of a full round of an object till comes back to the same position. In this case, the circle represents a single step of a walker. The sine function was used to generate simulated vertical foot positions and foot velocity. For the velocity, three different curves are shown representing different speeds. The kinetic energy is calculated from each velocity curve. Furthermore, three different vertical position lines are used to calculate the potential energy for all points. Finally, the average of total energy is taken from all total energies for all points.
Figure 3.3: Sine waves represent different velocities and vertical positions of feet

Figure 3.3 depicts the three different simulated velocity curves. All of the curves have the same general shape. Since the curves are meant to represent the physical position of feet, the blue line, the orange line and the grey line of the graph were shifted up by 1, 1.25 and 1.5 respectively in order to make foot location zero when it’s on the ground. As shown in the legend below of the graph, the blue line represents \( \sin x + 1 \). The maximum velocity for the orange line (\( \sin (0.75 \times x) + 1.25 \)) is 25% greater. The maximum velocity represented by the grey line (\( \sin (0.5 \times x) + 1.5 \)) is 50% greater than the original curve. If we look at the blue line (\( \sin x + 1 \)), its output starts from zero then increases to two. This part of the curve represents the beginning of the swing phase when the foot is on the ground and starts lifting up. The velocity will increase to its highest value while foot is going upward. Then, the velocity curve is decreasing and when the foot hits the ground the velocity will become zero again. Each of these curves represent two walking steps.

The kinetic energy is calculated for all points and then the average was taken. The output of the blue line (the original) is 0.738461538 while the output of the orange line (25% bigger than the original) is 1.162790702 and the output of the grey line (50% bigger than the original) is 1.700787196. These results indicate that when the curve is 25% bigger, the kinetic energy is one and a half times more. When the curve is 50% bigger than the original, its kinetic energy is 2.25 times more. This changing scale reflects exactly the equation of kinetic energy since the velocity is squared. Clearly, we can see that when the velocity becomes bigger then the kinetic energy is also bigger.
The process of simulating the vertical position or height of the feet is similar to the velocity. Figure 3.3 also shows the simulated vertical positions of the foot that were generated using the sine function. The blue line is the output of sin x +1 and represents when the user walks in a normal speed and lifts his/her feet to a normal height. The orange line is the output of sin (0.75 *x) +1.25 and represents a walk when the simulated step height is 25% higher than the original line. The grey line is the output of the equation sin (0.5*x) + 1.5 and represents when the walking steps with heights that are 50% higher than the original. The graph shows two walking steps per line. The higher steps go further in distance than the original and the vertical positions are also higher.

The potential energy is calculated for each point then the average of all points is taken. The average energy of the original line is 9.64923077 while the average of the orange line (25% greater than the original) is 12.1552485 and the average of the grey line (50% greater than the original) is 14.81519067. The results show that when the step is 25% higher, the average potential energy is 25% more, and when the step is 50% higher, the average potential energy is 53% more. Therefore, we clearly see that when the steps are higher it results to greater values in the potential energy.

<table>
<thead>
<tr>
<th>Step</th>
<th>Kinetic energy</th>
<th>Potential energy</th>
<th>Total energy</th>
<th>Total energy changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>0.738461538</td>
<td>9.649230769</td>
<td>10.38769231</td>
<td>100</td>
</tr>
<tr>
<td>Orange</td>
<td>1.162790702</td>
<td>12.1552485</td>
<td>13.3180392</td>
<td>128.21</td>
</tr>
<tr>
<td>Grey</td>
<td>1.700787196</td>
<td>14.81519067</td>
<td>16.51597787</td>
<td>159.00</td>
</tr>
</tbody>
</table>

Table 3.1: Synthetic data that represent velocity changes in virtual reality

In table (3.1) the total summery of the synthetic data is shown. The Total energy changes column indicates how much the total energy will change as a function of the original line. As we can see, the blue line is changing 100% which means the velocity will be the same in virtual environments. While in orange line which is 25% greater than the original one, the total energy will be higher by 28.21%. The velocity for the grey line which is 50% greater is higher by 59%. As the table shows, most of the energy is potential energy. Therefore, even if the user walks normally but lift his/her feet up will consume a good amount of energy that makes him/her feel the virtual slope.

3.5 Scaling Virtual Movement Based on Relative Energy Output

Total mechanical energy can be used as a measure of current walking effort. If the effort of the user walking normally on a level surface is used as a reference, the current walking effort can be used to determine if the user is exerting themselves additionally when attempting to climb a virtual slope. The kinetic energy term accounts for increases in walking speed or walking a greater
distance. The potential energy term accounts for exaggerated foot motions such as lifting the feet higher. Given the slope of a virtual incline, we can determine the additional walking effort that will be needed to go up or down the slope while maintaining a constant speed. The additional walking effort that will be necessary relative to the reference can be determined based on a curve as depicted in Figure 3.7. The virtual walking speed is relative to user movement in the real world. Any movement in the real world influences walking speed in the VE. Virtual walking speed is based on the current walking effort relative to the reference walking effort and the slope of the any virtual incline over which the user is navigating.

In order to scale virtual walking speed, a measurement of the walking effort on a level surface is needed. The measurement will act as a baseline reference to determine when additional walking effort is being made. To obtain this reference, the user walks normally on a level surface. This period gives a specific average energy that differs from one user to another, depending on their walking norm, gait, speed, and how high she/he lifts their feet up. The period of time could be 30 seconds to one minute.

The instantaneous total mechanical energy of the feet will vary significantly depending on where the individual feet are in the gait cycle. To smooth the response of the system, a running average of the current walking effort is used to scale the virtual walking speed. The running average is updated each frame and is used as the mechanical energy (work) when scaling virtual walking speed.

Slope is calculated by getting the angle that is made by comparing a vector representing the horizontal component of the virtual travel direction and a vector that is normal to the virtual terrain. In figure 5.2, the black arrows are the normal vectors. They are perpendicular to the terrain at each point. The red vectors illustrate examples of horizontal direction of travel vectors. The angle made between the direction of travel vector and the normal vector can be determined by taking the dot product of the two vectors [25]. If the dot product is positive the incline is negative and the slope angle is given by

\[
slope \ angle = -\cos \left( \frac{n \cdot d}{|n| \cdot |d|} \right)
\]  

(3.6)
where \( \mathbf{n} \) is the normal vector for the virtual terrain at the current virtual position and \( \mathbf{d} \) is the horizontal direction of travel vector. If we take left hand slope, let’s assume the angle between normal vector and travel vector is 45 degrees and assume both are unite vectors. Thus, dot product would give us \( \cos 45 \) and \( -\cos \) would give us \(-45\). Therefore, we know that we are going over a negative incline. If the dot product is negative, the incline is positive and the slope angle is given by

\[
slope\ angle = -\cos \left( \frac{\mathbf{n} \cdot \mathbf{d}}{|\mathbf{n}| \cdot |\mathbf{d}|} \right) + \pi \tag{3.7}
\]

If we take right hand slope this time and, let’s assume the angle between normal vector and travel vector is 135 degrees and assume both are unite vectors. Thus, dot product would give us \( \cos 135 \) and \( -\cos + \pi \) would give us 45. Therefore, we know that we are going over a positive incline. In case if we have angle \(-90\) degrees or 90 degrees for both equations respectively, we know that we are walking on level ground. The angle is converted to a gradient measure for use in scaling the virtual walking speed the gradient of the incline is given by

\[
gradient = \tan (slope\ angle) \times 100.0\% \tag{3.8}
\]

In order to scale the virtual walking speed, it is necessary to calculate a slope factor. The slope factor will vary based on the incline of the virtual terrain in the virtual direction of travel. On virtual terrain that is level, the slope will be equal to one. When the user is going up a positive incline, the slope factor will be less than one. If an incline is slightly negative, the slope factor will be greater than one representing the reduced work need to walk in the direction of a gently downward slope.

The slope factor can be determined based on a “cost of walking” curve show in Figure 3.5 [26]. This curve is based on the fifth degree polynomial

\[
C_w = 280.5(i)^5 - 58.7(i)^4 - 76.8(i)^3 - 51.9(i)^2 + 19.6(i) + 2.5 \tag{3.9}
\]

Where \( i \) is gradient, \( i \) should be a value between 0.0 and 1.0. This equation provides the cost of walking on gradients ranging from \(-45\%) to 45\% in centiwatts (Cw). The multiplicative increase or decrease in the amount of energy needed to go up or down a slope can be found by taking the ratio of the cost to walk on a particular gradient to the cost to walk on a level surface. The ratio is shown by the lower curve shown by the red dashed line in the same figure. Therefore, energy ratio is equal to \( C_w/2.5 \) since in level ground the output of the \( C_w \) is 2.5. For instance if the gradient was 10\%, this energy ratio would be equal to approximately 2, indicating that twice as much energy is
needed to walk up a 10% grade without a change in walking speed. Based on this ratio, the slope factor is given by

\[
\text{slope factor} = \frac{\text{current walking effort}}{\text{energy ratio(}
\text{reference walking effort})}
\]  

(3.10)

Where reference walking effort is average energy which is added total energy of a user for a certain amount of time divided by the time. The slope factor can then be used to modify the virtual velocity based on the physical walking speed using

\[
\text{virtual walking speed} = \text{slope factor} \cdot \text{(physical walking speed)}
\]  

(3.11)

This means the virtual walking speed depends on the current walking effort and the slope. If the user consumes more energy by lifting his/her feet up or walking faster the slope factor will increase. If the current walking effort is less than the product of the energy ratio and the reference walking effort, the virtual walking speed will be less than the physical walking speed. In contrast, if the user expends more energy by lifting their feet higher but does not increase their physical walking speed, they will observe an increase in their virtual walking speed.

Table (4.1) illustrates different cases depending on energy and slope. In this table we illustrate some cases and present how the virtual speed would change depending on equation 3.9, 3.10 and 3.11. We assumed that current walking effort and reference walking effort are 10 Joules. As shown, if the slope is 0 percentage, the output of the virtual speed is one, which means since the current walking effort and reference walking effort are the same and slope factor is 1, thus, the virtual speed will be as the physical speed. The values of virtual speed indicate how many times more we need to change the speed in order to reflect the energy and slope effects.

![Figure 3.5: Energy cost of walking as a function of slope](image-url)
<table>
<thead>
<tr>
<th>Grade</th>
<th>Current walking effort</th>
<th>Reference walking effort</th>
<th>Energy ratio</th>
<th>Slope factor</th>
<th>Physical speed</th>
<th>Virtual speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.45</td>
<td>10</td>
<td>10</td>
<td>1.442027688</td>
<td>0.693468</td>
<td>1</td>
<td>0.693467961</td>
</tr>
<tr>
<td>-0.4</td>
<td>10</td>
<td>10</td>
<td>1.401664</td>
<td>0.713438</td>
<td>1</td>
<td>0.713437743</td>
</tr>
<tr>
<td>-0.35</td>
<td>10</td>
<td>10</td>
<td>1.174577813</td>
<td>0.85137</td>
<td>1</td>
<td>0.851369734</td>
</tr>
<tr>
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<td>10</td>
<td>0.883006</td>
<td>1.132495</td>
<td>1</td>
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</tr>
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<td>1</td>
<td>1.622820919</td>
</tr>
<tr>
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<td>10</td>
<td>0.434688</td>
<td>2.300501</td>
<td>1</td>
<td>2.300500589</td>
</tr>
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<td>10</td>
<td>0.374373063</td>
<td>2.671132</td>
<td>1</td>
<td>2.671132355</td>
</tr>
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</tr>
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</tr>
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<td>3.150976</td>
<td>0.317362</td>
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</tr>
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<td>1</td>
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<td>10</td>
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</tr>
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<td>10</td>
<td>10</td>
<td>7.040118813</td>
<td>0.142043</td>
<td>1</td>
<td>0.142043057</td>
</tr>
</tbody>
</table>

Table 3.2: Channing virtual speed as a function of current walking effort and slope

When the terrain gets steeper more energy is needed to keep the same virtual speed as the physical speed. In this case, the energy is the same, therefore, the speed gets lesser and lesser as we go up to higher incline. However, for the same energy when we walk on negative incline and we keep the same amount of energy the virtual speed increases, as we get more negative incline the virtual speed gets decreased since we need more energy to push ourselves up when we walk down in such negative inclines. This table clearly shows us how the perspective virtual speed would change based on the current walking effort and slope.
3.6 Summary

Total mechanical energy can be used as a measure of current walking effort. If the effort of the user walking normally on a level surface is used as a reference, the current walking effort can be used to determine if the user is exerting themselves additionally when attempting to climb a virtual slope. This in turn can be used to scale their walking speed in an immersive virtual environment. As shown in table (3.2), the virtual speed has a strong relationship with current walking effort and slope that the user is currently walking on.
4 Experiments

4.1 Experiment description

The following experiments were conducted to investigate whether the effort associated with walking up slope or walking with increase speed could be measured using foot mounted inertial/magnetic sensors. Normally, when we walk fast or lift our feet up, we feel that we are consuming more energy and we experience fatigue. Using foot mounted inertial/magnetic sensors in this experiment, we gathered data related to energy and power consumption that might be used to simulate virtual slopes.

The experiment involved 12 participants; 9 males and 3 females. Their ages were between 20 and 39 years old. Their weights ranged between 135 pounds and 215 pounds and their heights were in range 5’4” to 6’2”. All participants were asked to walk on a treadmill as they do during normal exercise. Eight out of 12 experimental trial were done using Woodway brand treadmill and the remainder were done using True Fitness brand. No attempt was made to verify accuracy of the speeds and inclines of either treadmill. Inertial/magnetic sensors (see section 3.1) were attached to the participants’ shoes (underneath the laces) and the participants were asked to walk on the treadmill while the researcher recorded data using a laptop connected to the sensors as shown in figure 4.1.

Each participant walked on the treadmill under 20 different conditions. Each condition involved a different combination of speed and incline. Speeds ranged from one to four miles per hour and inclines ranged from zero to fifteen grades. The combinations used in each of the conditions are
shown in figure 4.2. The participants walked for 30 seconds in each of the 20 conditions. The conditions were presented to each of the participants in the same order. Combinations involving a speed of 2.2 miles per hour were included in order to have data for a speed that was near 1 meter per second and would be comparable to other research. The overall aim of the experiment was twofold. The first was to establish that walking energy output associated with either increased speed or greater step height could be measured using foot mounted inertial magnetic sensors. The second was to obtain relative baseline measurements of the energy and power for each of the combinations that could be used to simulate slopes in VR.

![Figure 4.2: Data points shown on the treadmill for different speeds and inclinations](image)

Data were collected using algorithms that were incorporated into the HIVE-API. The HIVE-API is an Application Program Interface (API) that was implemented to support HIVE (Huge Immersive Virtual Environment) research [27]. The HIVE-API incorporates both physical and virtual devices. Physical devices are those devices that represent hardware devices, while virtual devices represent software devices. All physical and virtual devices are configured in such a way that output data are collected in a virtual device called “Head”. For the experiments, the Head output modified SCIFT data that included the instantaneous energy and power output. In a complete virtual simulation of slopes, the data output by the HIVE-API would be supplied to a game engine such as Unity [28] or Unreal [29]. The game engine would be responsible for rendering the virtual world visually. Scripts within the game engine application would manipulate virtual walking speed based on the supplied instantaneous power and energy data. Throughout the experiments described in this chapter real-time estimates of kinetic, potential, and total energy were produced and written to output files at 125Hz. In addition, all raw sensor data was written to output files at the same rate for possible reprocessing using modified algorithms.
4.2 Data Analysis

The approach for simulating virtual slopes described in the thesis is dependent on the ability to measure the relative energy output associated with walking on slopes. Total energy output consists of the sum of kinetic energy and potential energy. Since kinetic energy depends on velocity, it represents how fast the object is moving; in this case, the feet. Also, because the potential energy depends on the vertical height, it represents how high the object (the feet) are being lifted. The following will examine all variables related to the final calculation of total energy and power. In all calculations of mentioned variables, the average values are taken. That is, after collecting all 240 data files, 20 files for each participant, a simple program was used to collect average values from those files and place the output in different files for velocity, height, kinetic energy, potential energy, total energy and power. These were analyzed using Microsoft Excel.

4.2.1 Total energy

As shown in equation (3.5), total mechanical energy is the summation of the kinetic energy and the potential energy. Figure 4.3 illustrates how much total energy is being consumed for each of the tested combinations of slope and speed. The horizontal axis represents speed (mile/hour), and the vertical axis represents total mechanical energy (Joules) associated with the speed. Each colored curve shown in the graph represents the total energy values for different slopes. The data presented in figure 4.1 represent the 20 combinations that each participant was subjected to. Each data point is the average of the measured energy output for all of the participants.

By looking at the curves, we can notice that, regardless of the slope, all curves almost have the same patterns and values. The expectation of energy output is that the energy has to have higher values when there are higher speeds and/or steeper slopes. However, we can notice that all curves have approximately the same value at each velocity point regardless of slope. Obviously these results are not what is expected. Thus, this process needs more analyzing. To confirm that the total energy is correct, the kinetic energy and the potential energy have to be correct. Therefore, both energies will be examined separately and analyzed.
4.2.2 Kinetic Energy

Equation (3.1) indicates that velocity is the only factor that affects kinetic energy calculation if mass is assumed to be constant. Therefore, the plot of the kinetic energy is expected to be similar to the pattern of the velocity plot. Figure 4.4 depicts the average kinetic energy. The positive slope of all curves indicates that energy output increases as slope increases. Since the curves all have the same shape and height regardless of slope, it appears that the kinetic energy measurement is not impacted by slope because it’s related to the velocity not the vertical height.
4.2.3 Velocity

SCIP'T reads three dimensional acceleration from the IMMU sensor in body at and update rate of 125Hz. Based on the acceleration, angular rate, and magnetic data provided by the sensor, SCIP'T produces an orientation estimate. The orientation estimate is used to transform the acceleration measurements from body coordinates to an Earth fixed reference frame. Trapezoidal integration of the acceleration vector is used to obtain a three dimensional measurement of velocity relative to an Earth fixed reference. Speed is equal to the length of the velocity vector. Horizontal speed for comparison with treadmill two dimensional speed is determined by discarding the all vertical velocity components and is given by

\[ |v| = \sqrt{(x_1 - x_0) + (y_1 - y_0)} \]

The average velocity for a particular trial is given by

\[ \bar{v} = \frac{\sum_{i=1}^{n} |v_i|}{n} \]

where \( n \) is the total number of samples for that trial.

As shown in figure 4.1, experimental trials were conducted at speeds of 1, 2, 2.2, 3 and 4 miles per hour. Table (4.1) compares the treadmill speed as measured velocity by SCIP'T. SCIP'T speed is the average of speeds for all inclinations, while Treadmill is the speed that was indicated by treadmill. Treadmill speed was measured in miles per hour, while SCIP'T was calculated by meters per second. The conversion is shown in the table as well.

<table>
<thead>
<tr>
<th>Treadmill (miles/hour)</th>
<th>Treadmill (meters/second)</th>
<th>SCIP'T (meters/second)</th>
<th>Difference (percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.44704</td>
<td>0.537433</td>
<td>16.81938</td>
</tr>
<tr>
<td>2</td>
<td>0.89408</td>
<td>0.989517</td>
<td>9.64482</td>
</tr>
<tr>
<td>2.2</td>
<td>0.983488</td>
<td>1.082565</td>
<td>9.152092</td>
</tr>
<tr>
<td>3</td>
<td>1.34112</td>
<td>1.408323</td>
<td>4.771863</td>
</tr>
<tr>
<td>4</td>
<td>1.78816</td>
<td>2.062795</td>
<td>13.31373</td>
</tr>
</tbody>
</table>

*Table 4.1: Comparison between actual velocity from treadmill and velocity calculated by SCIP'T-API*
Figure 4.5 shows the graph of the average speeds from table (4.1). The curve with label “Level” indicates the speed measured by SCIPT when the users walk on treadmill with 0 percentage inclination. Treadmill is treadmill speed and SCIPT is the average of the combination of all speeds regardless of the slope. While there appears to be a systematic difference, the curve representing the speed output from SCIPT is similar in shape and height to the speed to which the treadmill was set. Both table (4.1) and figure 4.5 clearly show that we have overall a difference between the indicated speed of the treadmill and the speed measured by SCIPT. The difference is 16.81% when the speed is one mile per hour and 13.31% when the speed is four miles per hour. For other cases, there is less difference, possibility indicating that the most consistent results are obtained at normal walking speeds.

Table (4.1) and figure 4.5 clearly have shown that how similar the velocity calculation is to kinetic energy. Hence, it can be assume that the velocity is correct and we can conclude our kinetic energy calculation is also correct.

As mentioned above, the velocity of SCIPT was calculated in two dimensions for comparing purposes to treadmill speed since its velocity is two dimensions. However, for calculating kinetic energy, three dimensional velocity was calculated. Figure 4.6 is similar to figure 4.5 except there is a greater different between the speed as reported by the treadmill and SCIPT estimate of speed. This is as expected since the inclusion of the vertical component of velocity can be expected to produce greater velocities.
4.2.4 Potential Energy

As stated in equation (3.2), potential energy has a direct relationship with the vertical position. Therefore, all curves have identical patterns as the vertical position, except the values of potential energy are greater. The same process is repeated to calculate potential energy as we did with kinetic energy. The average of the 30 second point was taken, then the average of all participants was taken as well. Figure 4.7 shows the average potential energy with different inclines and speeds for all participants.

Figure (4.7) tells us that the potential energy is almost the same for all inclinations. If we examine the curves for inclinations of 0 and 15 degrees, it can be observed that the potential energy estimates are close to each other despite the differences in slope. According to research [27] and
human observations, while we are walking on slopes, we lift our feet up higher. This should result in greater potential energy measurements. However, the results do not show this. Therefore, we know that there is some inconsistency. The vertical position has to be responsible for these outputs since it’s the only factor that changes the potential energy. Accordingly, the vertical position was analyzed. In next section the estimates for foot height (vertical position) will be discussed.

**4.2.5 Height (Vertical position)**

Three dimensional foot position estimates are obtained through the integration of corrected velocity [21]. Our data has shown that the vertical position is not always correctly calculated. In this section, we are going to examine the data of an individual participant to show how the vertical position contains errors and examine different approaches to reducing the errors. Also, using the same process as seen in previous discussion, we are going to present the average height of all participants together to give an overall view of the data. The figures below are taken from the participant’s trial when he was walking with no incline at a speed of 2.2 miles per hour (0.98 meters per second).

![Vertical position](image)

*Figure 4.8: Vertical position before correction.*

Inertial/magnetic sensor coordinate system is right handed, where thumb and index finger are \( x \) and \( y \) respectively, and the middle finger pointed to the ground is \( z \). When the sensor is attached to the foot, the positive \( z \) is pointing toward the ground. Therefore, when the user walks, we should observe only negative values of \( z \), and when the foot is on the ground, the output should be zero. As shown in the Figure (4.8), there are positive values indicating that the foot is below the ground.
Obviously, this is not correct because the user was walking on the level surface. We can fix this error by setting all positive values to be zero. The result of this step is shown in figure (4.9).

![Figure 4.9: Making all vertical positive values to be equal to zero](image)

Figure 4.9 shows that the errors are eliminated from figure 4.8. As it’s shown, there is no value above zero. By correcting these errors we are getting more realistic results compared to non-corrected data. Until frame 2593, we can see that the average of steps’ heights is about 7cm, while in the last half it is about 12cm. The highest step is about 21cm. For normal walking we usually lift our feet between 5cm to 10cm. There are some other samples that show the user has lifted up his/her foot more than 1 meter. We proposed that we could limit this error by using a threshold. For overall data collection process, we used 45cm as the threshold. However, due to the limited data points in this example, we used 15cm to illustrate the idea of applying the threshold. Figure 4.10 demonstrates the output after applying the threshold of 15cm.
Figure 4.10 illustrates the vertical position after eliminating positive z errors and all steps that have a higher value than the 15cm threshold. These two techniques for correcting data have given us more accurate output, though, there is still a lack of consistency in vertical position estimates. Since potential energy depends on height or vertical position in the calculation, accurate energy estimates are not possible. After trying these two techniques for certain samples without obtaining the expected output, we decided to not adopt these techniques.

Another problem with calculating height is that SCIPT doesn’t put the actual height in contribution. For instance, if the participant walks on the zero grade inclination or 15 grade inclination, it has the same results. We expected the height output would be greater if the inclination is greater since we lift our feet higher when we walk on an incline. The data also showed inconsistency in vertical position with different slope degrees.

Figure 4.11 illustrates the feet’s vertical position in different slopes and speeds. The graph shows that as the speed goes up, the feet get to a higher position which is expected. Though, the height level is not correct. All participants walked normally, and none of them lifted their feet 25cm as shown by the data. In addition, there was an inconsistency with height in that, regardless of the inclination, almost all curves that represent different slopes have the same output. If we look at the graph when the speed is 4 miles per hour, we can see when the slope is 5 grade it has the highest value. While when the inclination is 15 grades, it has the lowest value. The data shows us that we cannot rely on this output to calculate potential energy correctly.
Another factor that could be used to control virtual velocity is power. Power is the amount of energy being used in a certain time, in other words, it measures how fast the energy is being consumed [7]. Thus, the power has a strong correlation with energy and the output is expected to be similar. The same process is repeated for calculating average power. As shown in figure 4.12, the power patterns are similar to total mechanical energy curves’ patterns shown in figure 4.3 except the values are much higher. SCIPT runs with 125Hz, therefore, the delta time for each frame is 0.008 seconds. The energy for each frame was divided by the delta time to get the power for each frame. This process has made the total energy and the power to have the same pattern. In figure 4.3, the smallest energy value is almost 1.5 Joule, while the largest value is almost is 12.5 Joule. In figure 4.12, the smallest value of the power is almost 180 Watt, and the largest value is almost 1600 Watt. Therefore, by dividing the smallest and the largest power outputs by the smallest and the largest energy outputs respectively, we reach to a conclusion that, the values of power are 125 times bigger than the values of total energy, which represents the frequency of calculating power.
4.3 Summary

In this chapter the experiment for the thesis approach was explained and the experimental results were covered as well. For the experiment, 20 data points from different slopes and speeds were taken and total energy and power are calculated. Both total energy and power are considered as the two main factors to work with to reach the goal of the thesis approach. The data have shown that the velocity and the kinetic energy were consistent to simulate how fast the user is walking. However, the data have shown that there is inconsistency with vertical position which leads to inconsistency in potential energy. Therefore, there is inconsistency simulating how high the user has lifted his/her feet up. This inconsistency in the potential energy has caused a deviation in total mechanical energy and power.

Figure 4.12: Describes the power of different speeds and inclinations
5 Conclusion

5.1 Overall conclusion

The use of natural walking as virtual reality locomotion interface can help to create a feeling of “presence”. Though, it may not offer the realistic walking sensations, especially when the virtual environment is hilly and has a lot of ups and downs, the lack of simulating slopes deprives the user of being really present in the virtual world. The ultimate goal of this research was to manipulate the virtual environment interface in a manner that would cause users to change their behavior when slopes are present in a synthetic world. For example, causing the user to choose the less steep and longer road over a steeper and shorter one.

In this thesis we have attempted to create a realistic way to simulate slopes. The approach was to estimate the energy and power output of the user while walking. Increases in the energy output associated with walking would cause the user to move up virtual slopes more quickly. It was anticipated that increases in walking speed would produce measurable increases in kinetic energy and that taking exaggerated steps by lifting the feet higher would produce measurable increases in potential energy. Experimental results indicate that kinetic energy can be successfully calculated using data from foot mounted inertial measurement units. However, there were inconsistencies in the calculation of the potential energy. Therefore, further research will be needed to determine the cause of the inconsistencies and accurately calculate potential energy.

The inconsistencies in potential energy estimation were discovered through a series of experiments. In the experiments, energy output was estimated for 20 different speed/incline combinations for each experiment participant. The collected data clearly show that velocity and kinetic energy were calculated accurately as illustrated in figure 4.3 and figure 4.4. The data also illustrate that potential energy estimates were inaccurate and lacked consistency. These inconsistencies where found to be the result of the inability of the Self Contained Inertial Position Tracking (SCIPT) system used in this research to accurately calculate foot height as illustrated in figure 4.11. Accordingly, in the future work section of this chapter, suggestions are given for those who want to build on this study to reach the ultimate goal of simulating slopes and producing changes in human behavior in virtual reality that reflect behavior on real-world slopes.
5.2 Contributions

The contribution of this thesis research include the following:

- Development and testing of a real-time algorithm for measuring energy output for measuring relative energy output during natural walking.
- Experimental evaluation of the algorithm using data from foot mounted inertial/magnetic sensor modules.
- Data analysis that indicates relative kinetic energy output can be accurately measured using velocity estimates from the SCPIE system.
- Data analysis that indicates vertical foot position estimates are inconsistent and cannot be used to accurately measure relative potential energy output.
- Development of an algorithm for scaling translational movement based on kinetic and potential energy output relative to baseline measurement taken for walking on a level surface.
- Therefore, more research is needed to obtain the corrected vertical position and potential energy, thus, the process that is described in the future work section could be done very smoothly.

5.3 Future work

The result of this thesis could be taken as a starting point for future work regarding slope simulation in the virtual reality. After SCPIE is fixed to calculate vertical position and potential energy correctly, this approach and the whole process would be a very good station to start from. In this section, a possible scenario of the future work is given in detail. This scenario was meant to be implemented at the first place. However, since we discovered the potential energy is being calculated incorrectly, this could be applied after the correct result is obtained. This future work would be a valuable research to simulate slopes realistically in the virtual world. Moreover, it would be an effective way to change user’s behavior in hilly environments.
5.3.1 Experiment to Determine the Effectiveness of the Slop Simulation

As stated previously, the goal of slope simulation in virtual environments is to produce changes in human navigational behavior that make those that are observed in the real-world when humans must navigate across sloped terrain. The following is a description of an experiment that could be used to determine the effectiveness of slope simulation in a virtual environment that utilizes a natural walking locomotion interface. This experiment was developed as part of this thesis. Due to problems in accurately measuring potential energy output, it was not carried out.

The effectiveness of slope simulation could be conducted in a virtual environment with three different walking trials. Each trial would require an experimental participant to travel from a starting point to a series of waypoints across different virtual topography. To minimize confounds associated with participants becoming confused about the location of the next way point to be reached, each would be marked unmistakable manner with a visual indicator that could be observed at a great virtual distance. Each trial might have multiple way points to reach, the visual indicator would always indicate the next waypoint. After getting the first waypoint, the visual indicator would move to the next destination. Destinations could be buildings, trees, statues, water fountains, etc. The primary goal would be to present that participant with multiple options for navigating across sloped terrain to reach the next waypoint. Defined paths to the next waypoint such as roads or trail would be avoided.

The purpose of having a variety of options is to let the participant freely choose what route she/he desires to follow to the next waypoint. Figure (5.1) illustrates trials of the experiments in the virtual environment. Each participant would complete the waypoint navigation tasks under three different effort conditions. The order of the conditions would be randomized and each would require a different amount of effort to navigate up and down slopes in the environment. The three different effort conditions as follows;
- No slope contribution; here, we are completely neglecting slopes and considering hills as a level ground. The user doesn’t need to work harder in hilly environments to cope them. The energy consumption will be as if the user walks normally on a zero elevation terrain.

- Realistic slope contribution; in this condition, slopes are considered in calculation as they are in virtual environments. The energy consumption differs between level ground areas and sloppy areas. Energy consumption is determined according to the energy consumption equation graph that is shown in figure (5.6).

- Exaggerated slope contribution; in this case, slopes are exaggerated by a certain percentage more than what really exist. The user needs to consume more energy than real world to climb up the slopes. Basically this condition is the same as previous condition other than we are exaggerating the slope.

The goal of having a variety of slope contribution is determination of how realistically slopes change user’s behavior to reroute accordingly. With no slope contribution condition, the expectation is that, the participant will not take slopes into consideration and would choose any direction or the shortest path regardless of the terrain topography. While in realistic slope contribution, the participant is expected to take slopes into consideration, because the participant will feel that walking on less elevated terrain is easier than a steep one. Therefore, slope should change user’s behavior to choose a long road with less slope rather than a short and steeper one. The exaggerated slope contribution condition has the same impact as the realistic slope contribution, as a consequence, the expectations are similar with exaggeration. In this condition, the participant is expected to avoid slopes more than the two previous conditions. At the end of each experiment, the virtual position and slope data will be written to an external file and then will be compared with virtual position and slope of other experiments with a different slope contribution. Consequently, we can see if the user has taken a different route as a function of slope and made the user to change his/her way accordingly.
References


