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The First Step Toward the Future of Wearables in Rehabilitation

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Abstract

Tibial stress fractures are a major problem for runners and military athletes due to the high-intensity nature of their training. This injury is commonly treated through subjective measures including rest and management of symptoms that are evaluated by a therapist or trainer. With the advancement of technology such as inertial measurement units with accelerometers, clinicians may have the potential to provide an objective way to rehabilitate tibial stress fractures. Wearable technology is becoming more popular to be used in training but has not made it to rehabilitation yet. This study examines the validity of derived measures from the IMeasureU IMU compared to forces calculated from a validated 3D motion capture system during a running task. It was found that an IMU placed on the low back provided good to excellent correlations (0.776-0.972) between IMU derived measures and ground reaction and joint forces. Utilizing IMUs may provide clinicians with a tool to track loading over time, tailor protocols to individual athletes, and possibly heighten the rehabilitation process.

Keywords: inertial measurement units (IMUs), tibial stress fractures, wearable technology

The First Step Toward the Future of Wearables in Rehabilitation

Tibial stress fractures are a problem for military and civilian populations alike.[1,2,3] An estimated $585 million from the Department of Defense (DOD) is lost due to lower extremity musculoskeletal injuries in basic combat training (BCT) cadets. Individuals are entering at lower physical activity levels than ever, leading to a high incidence of stress fractures and subsequently soldiers restarting and being discharged from training.[3,4] A study analyzing BCT soldiers from 1997 to 2007 showed the incidence of lower extremity stress fractures to be 6.9 per 1,000 men and 26.1 per 1,000 women.[5] The rapid and intense shift in load bearing for these individuals overwhelms the physiological systems and causes injury.[1,6] Load or biomechanical loading can be defined as the combined stress due to activity in practice or work placed on a person's body.[7] In the case of tibial stress fractures, interest lies in how the external load, acceleration of the tibia, impacts the internal load or the physiological response.[6] One way the military is trying to help combat this spike in workload is by extending training significantly. There is currently a pilot program being tested on a new class of infantrymen at Fort Benning in Georgia where soldiers attend training for 22 weeks instead of the normal 14 weeks.[8] Regardless if individuals are eased into training, soldiers still have to run and, just like civilian runners, some will be plagued by tibial stress fractures. This injury makes running and other athletic tasks difficult, painful, and, in some cases, too excruciating to bear. All stress fractures in the body, regardless of location, occur in the same way. There is too much load being placed on the bone due to a high intensity of training causing miniscule fractures in the bone that heals slower than injury is occurring.[2] Furthermore, inadequate management of load on the body during training could be a risk factor for injury.[9] It has also been shown that a previous tibial stress fracture injury can make an individual six times more likely to have a repeated injury.[10] Treatment and prevention of tibial stress fractures essential for those participating in high impact training whether as part of sport or occupation.

The Need for Novel Treatment

Currently the treatment for tibial stress fractures includes rest, a gradual return to physical activity, and monitoring patient reported symptoms.[11] By using an estimate of how long it takes a bone to heal along with graded running protocols, it can likely reduce reoccurrence of tibial stress fracure.[12] Research has proven that resting and, in some cases, immobilization is the best way to heal a stress fracture but could take 4 to 6 months before a patient is able to return to activity.[1] Resting allows for the bone to heal properly before force is placed on it again. Gradual return to activity usually entails a 10% rule where the person does not exceed 10% more of the mileage completed in the previous week.[13] Based on knowledge of the body and healing processes, it makes sense to slowly return to full activity and monitor symptoms, but this method is based only on the clinician's evaluation of the patient and has not been adequately studied. This can be a problem because evaluations can differ between therapists and their opinions on how and at what rate patients should progress through rehabilitation may also be unique.[1,8,14] Clinicians have also been found to use distance over a certain amount of time to monitor the progression of work the patient completes in a training session.[11] Although found to correlate with loading on the tibia, this method does not provide an answer to how patients should progress through training. Also, every patient is unique and differences in biomechanical loading could impact how much loading is placed on certain parts of the lower extremities not accounted for when measuring running distance over the time on a treadmill. Too much load being placed on the body during training has shown time and time again to influence the occurrence of injuries sustained during running.[15]

There are a number of ways in which tibial stress fractures are managed and treated that is unique to each patient and therapist. Ideally, therapists would use an objective way to measure tibial loading to return patients back to prior physical activity levels with less risk of re-injury and in timely fashion. Unfortunately, this currently cannot happen without a validated way to measure the load placed on the tibia during an entire training session. This may be possible, though, with the use of wearable technology.

What are Wearables?

Over the past decade, the use of wearable technology has been increasing especially in the fields of exercise and movement analysis.[12] The term Wearables refers to any type of technology that an individual can wear that provides quantifiable data and is often used to measure different aspects of the state, motion, or response of the body such as heart rate monitors, body temperature sensors, steps counters, and even the acceleration of specific extremities using acceleraomters.[16] Wearables most often consist of three main parts: the sensor itself, software on an electronic device, and a web-based server created by the manufacturer.[12] Wearable technology has really hit the market of competitive sports and running where they have been used to track an athlete’s body during training, help tailor future training to maximize performance, and reduce injuries.[12]

Although used often and found to be useful in sports training, wearables are not commonly used in rehabilitation due to a variety of limitations. One of these limitations is due to lack of validity. If the technology does not accurately measure and report the desired metrics, then that piece of equipment is not useful. An effective wearable technology would need to produce values that correlated strongly to information useful to a therapist: the amount of stress being placed on a tissue such as bone, tendons, or muscles during certain tasks. Clinicians are also limited by a lack of normative data. If there is no normal sample or “healthy” values for comparison this makes it difficult to conclude that the individual’s results are good or bad. To elaborate further, a clinician will not be able to look at results and diagnose a patient without a standard of comparison. Diagnosis of tibial stress fractures, like other musculoskeletal injuries, is made by identifying a set of symptoms that others with the same disorder exhibit and other functional tests in which the response is consistent, i.e. pain or the inability to perform certain tasks.[11] Without the results from a population with stress fractures, for example, it is not reasonable for a clinician to be able to make a diagnosis or rehabilitation plan from data they obtain in a testing session. Another limitation of wearables is the amount of information they are able to give that cannot be utilized without a way to sort out and calculate the data they want.[12] Clinicians and users may have too much data to work with and interpret in order to make a diagnosis or understand what is happening with the body without a way to filter it.[12]

Finding a Solution

The way in which stress fractures of the lower extremity are treated has not been validated to measure the stress placed on this area. There is a need for a way to measure the load placed on the lower extremities during rehabilitation sessions. To do this, researchers need to explore their options to enhance rehabilitation to improve patient outcomes. One idea for measuring this load lays in a specific wearable called Inertial Measurement Units (IMUs). IMUs are small devices that contain an accelerometer, gyroscope, and magnetometer.[17] This allows the device to capture data related to acceleration, angular displacement, and orientation, respectively.[17] Accelerometer-derived measurements can be determined with the use of IMUs.[18] They hold the potential of creating values for an individual’s biomechanical loading during a training session based on acceleration. This output could allow clinicians to record an individual’s session and compare it to their previous in order to monitor change.[18] It could also serve as a guide in how further training sessions should progress and even help predict the best treatments for other patients.

At this time, therapists tend to use the distance a person moves over a certain period of time to get an idea of how much work the person is performing in each session to estimate the stress placed on the bone. Providing a way to measure each foot strike and how each foot strike accelerates and decelerates with IMUs, a clinician could see all the load placed on the bone and better track training sessions for stress fracture patients. Clinicians can then pair this knowledge with a consideration of the bone's response to stress and how quickly the healing process is.[19]

There are products on the market such as phone apps that claim to measure acceleration and other IMU capabilities that have not been validated. Although quick and easy to access, there is no way to know if these devices are accurately measuring biomechanical loading. The only way to be certain is through validity determined through certain movements. Walking and running, for instance, involve a slightly different movement pattern in which their validities must both be determined. Not only this, it is important that IMUs are not generalized in their validity. IMUs are sensitive devices and differ from manufacturer to manufacturer. It is extremely important that every type of IMU be studied for validity and reliability. Manufacturers rarely study the validity of their products making it necessary for labs to study each device metric in order to accurately interpret and utilize the product effectively.[18] Each device is unique in its overall makeup, the software used, and how results are shown. The IMUs created by IMeasureU (IMeasureU, Auckland, New Zealand; see Figure 1) are no different; there is a need to study the validity of the IMeasureU IMU because it has not been

Figure 1: IMeasureU IMU

completed before. To progress research or use the IMU in a clinical setting, the accuracy of the measurements must be determined.

The purpose of this study is to determine the validity of the IMeasureU IMU in measuring biomechanical loading on the tibia during walking, running, and walking with a weighted backpack (rucking) tasks. The hypothesis is that vertical and resultant cumulative loading metrics will be valid measures of tibial loading by demonstrating strong to excellent correlations with ankle, hip, and knee joint loading measures using three-dimensional motion analysis during over ground walking, running, and rucking.

Methods

This project is currently in progress at the Sports Medicine Research Institute (SMRI) at the University of Kentucky. There is a two-prong approach to this study: one being validity of IMeasureU IMU in measuring biomechanical loading on the tibia, chest, and low back and the second being the test-retest reliability of the IMeasureU IMU over a seven-day span. The focus of this paper will be on the validity prong of the study in which running was analyzed.

Testing Procedure

Participants were recruited through the local US Army and Air Force ROTC programs containing 200 cadets. Nine participants have completed both days of testing thus far. Each participant completed two testing sessions. Before testing began each participant signed an informed consent in accordance with the university Institutional Review Board. Once that was finished the participant had their height and weight measured. The first testing session contained a treadmill procedure and an over ground procedure. The treadmill procedure was completed first and involved the participant walking, running, and rucking wearing a 16.926 kg backpack in

Figure 2: IMU Placement on Tibia

random order for five minutes for each condition on a standard treadmill. Before data was collected for both procedures, the participants had IMeasureU IMUs (0.59 x 1.57 x 1.10 inches) placed on their distal medial tibia on both legs five centimeters above the medial malleolus (see Figure 2), the low back, positioned approximately at the spinous process of L4/L5, and the chest at the sternum sensor positioned at the distal aspect of the sternum. All sensors were secured using elastic straps. A single Delsys IMU (Delsys, Inc., MA, USA) was placed directly above the right tibia IMU. This allowed for the synchronization of the three-dimensional motion capture system with the IMeasureU IMUs. After the treadmill procedure, the participant was allowed to rest and then completed the over ground procedure. In this procedure the participant had reflective markers attached to them in specific anatomical and anchor positions on the feet, legs, and trunk (See Figure 3). The participant was then asked to stand with one foot each on the force plates two with their arms extended in a thirteen camera three-dimensional motion capture system (Vicon Motion Systems, Oxford, UK) for calibration. The medial joint markers, left knee, left hip, and ASIS markers were then removed from the body as they were only needed for calibration. The participant then walked, ran, or rucked in random order over the force plates. A practice trial was done to best determine the location of the starting line, so the participant would land one foot on each force plate. Once this was determined a cone was placed for the location for them to start. Cones were adjusted if good contact was not being made with the force plate. Before each trial began they were asked to stomp their right foot on the

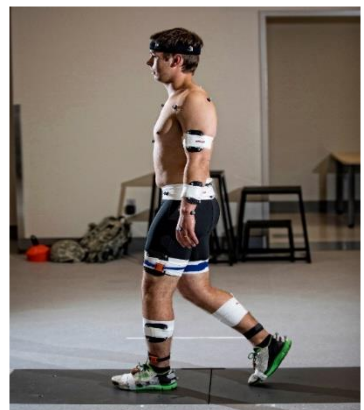

Figure 3: Marker Placement during Over Ground

ground and then proceeded to walk, run, or ruck at a pace similar to the one they performed on the treadmill. This stomp signal in both right tibia IMUs, IMeasureU and Delsys IMU, was used to sync the data between the IMUs and 3D motion capture system. The participant completed up to 10 trials for each condition until four complete contacts on both feet were achieved, completing all trials of the first condition before moving onto the next condition.

Data Processing

After all testing sessions, the four IMUs were connected to a computer to download the raw data. The data files and sync files were first run through a custom Matlab (Mathworks, Inc., MA, USA) Code "IMULapCut" to separate the data into each walking, running, and rucking trials. This parsed out trial output then needed to be synchronized with the 3D motion capture data. To do this the separated trial data was run through another Matlab code, "StompOffset," to calculate the time from the stomp signal to when the participant impacted each foot on the force plates. With this information acceleration-derived metrics were calculated using a third Matlab code, "IMUPeakAcc". IMU data processing was conducted using a custom Matlab script. For each trial, a second order, dual pass 50 Hz Butterworth low-pass filter was applied to acceleration data in all three axes (x, y, and z). Each IMU was analyzed for the peak acceleration during the step on the force plate associated, left and right foot respectively. Resultant accelerations were calculated by taking the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (Equation 1).

$$\text{Equation 1: } \sqrt{\left(a_y\right)^2 + (a_x)^2 + \ (a_z)^2}$$

The data from the Vicon Nexus 3D motion capture system was edited within the native software program for the markers to be labeled and calibrated with a pipeline model. Another software program called Visual 3D (V3D, by C-Motion Inc., Germantown, MD) was then used to load the trials of interest and calibration file to calculate the biomechanical variable from the force plate and 3D marker data. The metrics of interest were joint angles and forces for the ankle, knee, and hip and the vertical ground reaction forces calculated from V3D.

The accelerometer-derived metrics from the over ground procedure were compared to loading metrics from a previously validated 3D motion capture system during the same tasks using a Pearson's Product Moment Correlation Coefficient. If one of the variables was found to not be normally distributed from the Shapiro-Wilk Test for Normality, a Spearman's Correlation Coefficient was used. An alpha of 0.05 was set a-priori. All statistical calculations were completed in SPSS (IBM Inc., NY, USA).

Results

Nine participants completed both days of testing. Six participants' results were analyzed; 6 men; age: 29±7 years; height: 177.15±6.26 cm; weight: 86.93±7.58 kg. Three subjects were excluded due to missing data. The 3D camera systems were not collecting data for two subjects so their data could not be analyzed. The main correlations of interest were the vertical ground reaction forces compared to peak acceleration from the IMeasureU IMUs and peak acceleration compared to peak ankle, knee, and hip forces from V3D. The focus of this analysis is on the running data. Of all variables, the left tibia peak horizontal resultant ($p=0.027$) and the right y-axis max ground reaction force ($p=0.040$) were found significant in the Shapiro-Wilk test for normality, therefore correlation calculations for these values were analyzed using the Spearman's Correlation Coefficient. The categorization of correlation strength can be found in Table 1 and all the correlation results can be found in Tables 2-5. The good and excellent (>0.75) correlations are bolded in the result tables. All variables were also analyzed with the Spearman's Correlation Coefficient due to low sample size.

Table 1: Correlation Strengths

Category	Range
Excellent	0.9-1
Good	0.75-0.90
Moderate	0.6-0.75
Low	0.45-0.6
Little to None	<0.45

From the results in Table 2 and 3 it can be seen that the IMU chest variables produced negative correlations with all ground reaction force variables (-0.805 to -0.002), opposite of what was hypothesized. The right low back peak resultant (0.604 to 0.612) and peak y-axis (0.621 to 0.626) showed moderate correlations with ankle, knee, and hip forces. The left low back peak resultant (0.956 to 0.972, p values <0.01) and peak y-axis (0.781 to 0.798) showed good to excellent correlations with ankle, knee, and hip forces. The same variables showed good correlations with the max ground reaction force in the y-direction also (0.776 to 0.855). In the Spearman's Correlations right tibia peak resultant, horizontal resultant, and y-axis showed moderate to good correlations with the max ground reaction force in the y-direction (0.657-0.771). Those three variables also showed moderate to good correlations with ankle, knee, and hip forces (0.600 to 0.771).

<u>KEY</u>
BOLD: correlation > 0.75 or < -0.75 (good to excellent correlations)
*: p-value<0.05 **: p-value<0.01

Table 2: Pearson's Correlation-Right

Variable	maxGRF_R_y	maxGRF_R_z	maxGRF_R_mag	RAnkle	RKnee	RHip
Chest_Rt_peak_resultant	-0.599	**-0.804**	**-0.805**	-0.323	-0.326	-0.307
Chest_Rt_horz_resultant	-0.451	-0.573	-0.573	0.040	0.042	0.036
Chest_Rt_yaxis	-0.415	-0.606	-0.609	-0.319	-0.323	-0.304
LowBack_Rt_peak_resultant	0.363	0.407	0.408	0.626	0.624	0.621
LowBack_Rt_horz_resultant	-0.171	-0.072	-0.069	0.490	0.484	0.500
LowBack_Rt_yaxis	0.598	0.604	0.604	0.612	0.611	0.604
RTib_peak_resultant	**.822***	0.615	0.612	0.660	0.661	0.656
RTib_peak_horz_resultant	**0.794**	0.541	0.537	0.539	0.542	0.536
RTib_peak_yaxis	**.868***	0.709	0.707	0.636	0.641	0.628

Table 3: Pearson's Correlation-Left						
Variable	maxGRF_L_y	maxGRF_L_z	maxGRF_L_mag	LAnkle	LKnee	LHip
Chest_Lt_peak_resultant	-0.271	-0.549	-0.549	0.143	0.147	0.195
Chest_Lt_horz_resultant	-0.539	-0.559	-0.558	-0.093	-0.095	-0.084
Chest_Lt_yaxis	-0.002	-0.363	-0.365	0.245	0.252	0.306
LowBack_Lt_peak_resultant	**0.776**	0.618	0.618	**.956****	**.959****	**.972****
LowBack_Lt_horz_resultant	-0.546	-0.587	-0.586	0.048	0.049	0.089
LowBack_Lt_yaxis	**.855***	0.677	0.676	**0.781**	**0.786**	**0.798**
LTib_peak_resultant	0.668	0.319	0.317	0.442	0.445	0.449
LTib_peak_horz_resultant	0.671	0.343	0.341	0.385	0.387	0.384
LTib_peak_yaxis	-0.077	-0.113	-0.112	0.392	0.393	0.435

Table 4: Spearman's Correlation-Right						
Variable	maxGRF_R_y	maxGRF_R_z	maxGRF_R_mag	RAnkle	RKnee	RHip
Chest_Rt_peak_resultant	-0.657	**-0.771**	**-0.771**	-0.086	-0.086	-0.086
Chest_Rt_horz_resultant	-0.600	-0.714	-0.714	0.029	0.029	0.029
Chest_Rt_yaxis	-0.257	-0.371	-0.371	0.086	0.086	0.086
LowBack_Rt_peak_resultant	-0.086	0.371	0.371	0.600	0.600	0.600
LowBack_Rt_horz_resultant	-0.486	0.086	0.086	0.429	0.429	0.429
LowBack_Rt_yaxis	0.371	0.600	0.600	0.429	0.429	0.429
RTib_peak_resultant	0.657	0.543	0.543	0.600	0.600	0.600
RTib_peak_horz_resultant	0.657	0.543	0.543	0.600	0.600	0.600
RTib_peak_yaxis	**0.771**	0.657	0.657	**0.771**	**0.771**	**0.771**

Table 5: Spearman's Correlation-Left						
Variable	maxGRF_L_y	maxGRF_L_z	maxGRF_L_mag	LAnkle	LKnee	LHip
Chest_Lt_peak_resultant	-0.714	-0.600	-0.600	0.086	0.086	0.086
Chest_Lt_horz_resultant	**-0.771**	-0.657	-0.657	-0.143	-0.143	-0.143
Chest_Lt_yaxis	-0.257	-0.600	-0.600	0.029	0.029	0.029
LowBack_Lt_peak_resultant	0.486	0.600	0.600	**.943****	**.943****	**.943****
LowBack_Lt_horz_resultant	**-0.771**	-0.543	-0.543	0.143	0.143	0.143
LowBack_Lt_yaxis	0.600	0.371	0.371	0.543	0.543	0.543
LTib_peak_resultant	0.543	0.200	0.200	0.600	0.600	0.600
LTib_peak_horz_resultant	0.371	-0.086	-0.086	0.371	0.371	0.371
LTib_peak_yaxis	-0.486	-0.143	-0.143	0.429	0.429	0.429

Discussion

Current treatment of stress fractures usually involves monitoring of symptoms and utilizing a graded rehabilitation plan to ease the patient back into load bearing.[20] In the graded rehabilitation plans therapists may track the amount of time spent running to determined workloads completed in that session.[13] Unfortunately, this way of measurement is not adequate for measuring vertical ground reaction forces, joint angles and forces, and the load being placed on the tibia. In this study, the derived measures from the IMUs show potential in unlocking this information. Based on the data from this study, IMUs are trending toward validity in measuring vertical ground reaction forces and joint loading. The hypothesis for this study was that vertical and resultant cumulative loading metrics will be valid measures of tibial loading by demonstrating good to excellent correlations with ankle, hip, and knee joint loading measures using three-dimensional motion analysis during over ground walking, running, and rucking. This study has begun to show acceptance of this hypothesis but must be examined further.

Interpretation of Results

Despite having a small sample size, there are some worthwhile correlations to discuss. One to note is the negative correlations being found on the measures for the chest IMU. This suggests that the chest IMU may not be useful for estimating impact forces at the tibia. There is no certainty why this variable may be negative but could possibly be due to the way each participant handles load during the running task. When the body absorbs load, the chest is one of the last places it occurs. This could lead to a lower peak acceleration when running over the force plates. The ground reaction forces and joint forces are all from the lower extremity, not the upper body, which could lead to this correlation being negative. It is possible that someone could hit the force plate harder and absorb more shock on the lower body but not the upper. Another important trend to point out is the low back resultant and y-axis showing good to excellent correlations with the joint loading data. This could suggest that the low back IMU resultant and y-axis values could be predictors of the loading on these areas of the body and vertical ground reaction forces. The right tibia measures correlated moderate to good with the ground reaction forces and joint loading as well. Unfortunately, the left tibia IMU produced mixed correlation results including some negative values that should be analyzed with caution. Left tibia IMU data showed little to no and low correlations. The difference in left and right tibia data could be due to different running mechanics among the participants or possibly the low sample size. With this information the low back IMU seems to be the most valid.

An IMU that is valid in measuring vertical ground reaction forces and joint loading could be of use to a therapist. Only one step was analyzed in this study, but with a recording of all steps during a workout, the cumulative load could be determined.[16] A large prospective study analyzing the biomechanics of participants and the risk of lower extremity stress fracture during a 4 year follow-up period found that the people who had greater peak vertical ground reaction forces and weaker in knee strength were more likely to sustain this specific injury.[15] Another study found that tibial stress fracture patients had greater peak and average vertical loading rates during walking compared to uninjured controls.[21] Knee stiffness has also been found to be associated with increased vertical ground reaction forces and tibial shock which may have contributed to participant injury in this study.[22,23] When injured, patients tend to move differently than their healthy counterparts. Fortunately, these specific characteristics have the potential to be adjusted and worked on as a focus of rehabilitation plans.[1,23] IMUs could help predict these risk factors and potentially be a tool for return to running programs tailored to each patient and injury.

Limitations and Issues

In previous studies, the main way that body mechanics and joint angles were calculated required a large room containing a 3D motion capture system and extensive processing procedures. This procedure is simply not feasible in a normal physical therapy clinic and even more so in a military field setting. Validated IMUs could serve as a replacement for this piece of equipment in these settings where 3D motion capture is not possible. IMeasureU IMUs collect data on small IMUs placed in bands going around the desired part of the body and an iPad. They can possibly provide the clinician with the necessary data to understand what is happening to the body during a workout. As previously mentioned, a useful wearable has to produce data that a clinician can use, understand, and interpret without using too much time. Researchers could work on making the processing of data quicker and easier to work with than it is currently. Before wearables such as IMUs could be used in a clinic, researchers have to provide proof that these devices are capable of calculating metrics that a therapist would be interested in when treating a patient. Clinicians also must be aware of how to use these devices, have the proper equipment, and be able to interpret the results correctly.

Although results were achieved, reaching this point was no simple task. The IMeasureU system was not collecting at the desired sampling frequency within Vicon Nexus so a unique testing procedure was used. The participant had to have a Delsys IMU attached next to the IMeasureU IMU on the right tibia to accurately sync the data. This data was collected on Vicon Nexus, the program the Delsys IMU was synchronized with. The connection between the two IMUs allowed for the determination of which step was the same as the corresponding one on the force plate as well as the accompanying vertical ground reaction force. This fact made processing more of a challenge. Custom Matlab codes were created to separate each trial in the over ground procedure, calculate the stomp offset, and also to determine the peak acceleration from the stomp offset times. A recent update of the IMeasureU IMU to sync with the Vicon Nexus System has eliminated the need for this complex procedure in the future.

This study has looked at specific signals from the IMeasureU IMU and the results from unique calculations. The goal was to validate the measures derived from the IMUs. With only six subjects' data, it is difficult to make definitive decisions based on these results. It is helpful, though, to begin to see trends in the data and decide what would be the best steps to take in the future. The first step being collecting more data and utilizing the update on the IMeasureU system to make the synchronization step of this processing obsolete and processing simpler. With more data, the correlations of the data may become stronger but, more importantly, it will provide a better idea of the true trends.

From the data of six subjects, trends are already starting to develop. Small sample size is a limitation of this study. Only six individuals were analyzed. During data collection for one of the nine subjects collected, the right tibia IMU died before the over ground procedure. This made it challenging to calculate the stomp offset since it was based on the right foot stomp. Two other subjects completed testing but the 3D motion cameras were not collecting data during the over ground procedure. This made it impossible to create a 3D bone model for these participants and subsequently, made it impossible to calculate joint loading forces from visual 3D.

What's Next?

The next immediate step in this study will be to recruit more participants for this study to enhance and better observe trends. It is also important to continue with the reliability prong of the IMeasureU IMU during the treadmill procedure. Researchers and clinicians need to know if the IMUs are valid in determining desired measures, but it is also imperative that they know the equipment is consistent in its measurements from testing session to testing session. From there, there are a number of studies researchers could continue with IMUs. In this study the IMU was used in a controlled environment inside a lab. To create a better application for the desired population and settings, the IMU has to be tested either outdoors or in some gym-like setting. This study could involve healthy participants completing various tasks such as running, jumping, and hoping with the IMUs placed on the tibias and low back. From the validated loading metrics on the low back and possibly the tibia, researchers could calculate the loading on the lower body and tibia during the entire testing procedure. The tasks could be monitored and adjusted during different sessions to see if higher loading tasks correlate with higher loading on the tibia as calculated by the IMU. During all these processes it would also be useful for researchers to determine an easier way to process data, so this technology could be understood and used to monitor patients in real life.

Conclusion

Tibial stress fractures are a major problem and will continue to be as long as people are active and running, especially in a high impact environment such as the military. The traditional treatment of rest and recording of symptoms has been recommended and utilized for a long period of time. With the boom of wearable technology, tibial stress fracture rehabilitation may have an opportunity to improve upon current practices to use session specific data to help guide patients through rehabilitation in a more individualized approach. Although there are more steps and studies ahead before these devices are ready to use in the clinic to better treat tibial stress fracture, IMUs show potential in reaching this goal. This study has demonstrated the strong correlations between low back peak resultant and y-axis measures calculated from the

IMeasureU IMU to vertical ground reaction forces in the left y-direction and ankle, knee, and hip forces. Although further testing is needed, an IMU placed at the low back shows promise to minimize the overall system and provided the best results. It measures all steps during testing and has shown increased correlations and validity compared to the other IMUs. The world of athletics has been poking at the potential of wearable technology to make people faster and stronger and it is time for the world of rehabilitation to do the same to help people prevent injuries and heal faster.

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