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14. ABSTRACT Walking is a complicated task that requires the motor coordination across multiple muscles and joints to propel the body forward. A basic understanding on how we walk is important because this sets the criteria necessary for human-machine integration (e.g. powered exo-skeleton and prosthetic designs). Advanced study in human locomotion would benefit from the researcher being able to systematically control the physical, visual, and audio environments while gait measurements are recorded.

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Report Title

Final Report: An Integrated Gait and Balance Analysis System to Define Human Locomotor Control

ABSTRACT

Walking is a complicated task that requires the motor coordination across multiple muscles and joints to propel the body forward. A basic understanding on how we walk is important because this sets the criteria necessary for human-machine integration (e.g. powered exo-skeleton and prosthetic designs). Advanced study in human locomotion would benefit from the researcher being able to systematically control the physical, visual, and audio environments while gait measurements are recorded.

Specific Aim: To acquire and install a Gait Real-time Analysis Interactive Lab (GRAIL) from Motek Medical BV that will provide a dedicated solution for locomotor control research and education at Alabama State University.

Results: The GRAIL system has been acquired, installed, and is now able to collect data on human locomotion. We are now standardizing our operating procedures and integrating those procedures with other DoD centers (e.g. Center for the Intrepid, Walter Reed, etc.). We have also been collecting pilot data for grant applications and using the system for education and student research projects

Future plans: Finalize system optimization and perform cross-center validation trials with our partner DoD centers. Continue using the system for student driven experiments, student education, and expand our work on human machine integration.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received

Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

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Walking is a complicated task that requires the motor coordination across multiple muscles and joints to propel the body forward. A basic understanding on how we walk is important because this sets the criteria necessary for human-machine integration (e.g. powered exo-skeleton and prosthetic designs). Advanced study in human locomotion would benefit from the researcher being able to systematically control the physical, visual, and audio environments while gait measurements are recorded.

Specific Aim: To acquire and install a Gait Real-time Analysis Interactive Lab (GRAIL) from Motek Medical BV that will provide a dedicated solution for locomotor control research and education at Alabama State University.

Results: The GRAIL system has been acquired, installed, and is now able to collect data on human locomotion. We are now standardizing our operating procedures and integrating those procedures with other DoD centers (e.g. Center for the Intrepid, Walter Reed, etc.). We have also been collecting pilot data for grant applications and using the system for education and student research projects

Future plans: Finalize system optimization and perform cross-center validation trials with our partner DoD centers. Continue using the system for student driven experiments, student education, and expand our work on human machine integration.

Forward

We all know how to walk but we don't fully understand how we walk. Walking is a complicated task that requires the coordination of many different muscles controlling many different joints to propel the body forward and maintain balance simultaneously. This is all being controlled by our nervous system and largely mediated in the spinal cord. A basic understanding on how we walk is important because this sets the criteria necessary for the creation of mechanical solutions that attempt to mimic and interface with a human being (for example, powered exo-skeletons, prosthesis, etc.). In addition, research in control of locomotion (walking, running, or cycling, etc.) is particularly challenging because this control is largely regulated in the spinal cord and we are limited to non-invasive methods (invasive methods like, implanting electrode arrays in the spinal cord, is not conducive to subject health).

The Biomechanics and Motor Control Laboratory at Alabama State University is focused on non-invasive methods to define human movement control. The nervous and musculoskeletal systems must interact with the environment to perform a movement. Therefore, we measure physiological and biomechanical outputs (muscle activity, joint forces) while controlling the environment and movement task. We then apply advanced mathematical techniques to derive the underlying motor control strategy. This fundamental control strategies my then be use to predict how a human will respond to different environments and this could include working in parallel with a powered exo-skeleton system.

The Gait Real-time Analysis Interactive Lab (GRAIL) system acquired through this grant will support Department of Defense (DoD) research interests through describing fundamental locomotor control principles. These principles are critical to the development of Brain Computer Interface (BCI) technology and DoD projects involving Human-machine interaction (for example, powered exo-skeletons, prosthesis, etc.)

Specific Aim: Acquire and install a GRAIL from Motek Medical BV that will provide a dedicated solution for locomotor control research and education at Alabama State University.

Results: We were granted \$484,000 to install a GRAIL system. The GRAIL uses an instrumented dual-belt treadmill, a motion-capture system, and within a synchronized Virtual Reality (VR) environment. This unique combination provides a powerful non-invasive method to control the environment and movement tasks while measuring the body's response. Alabama State University has contributed \$18,400 for room modifications and has purchased a three year service contract for \$56,000 to cover support and system maintenance.

The GRAIL system has been acquired, installed, and is being used to collect data on research projects and student education. We have integrated this system with our existing motion capture, force measurement, electromyography equipment.

Future plans: Continue optimizing the system for data collection. This includes optimizes the motion capture system, data collection/reduction protocols, and installation of additional software/ hardware. We completed two student driven experiments to optimize the orthotic

design for people with spinal cord injury and a prosthesis emulator design that relate to larger work on human machine integration.

Statement of the problem studied

The installed GRAIL system will advance Department of Defense research interests through describing fundamental locomotor control principles. These principles are critical to the development of powered exoskeletal systems that integrate with a human controller/operator. For example, have you ever helped someone up out of a chair and up expected them to pull against you more than they did? For a couple seconds, both of you attempt to adjust your pull until either the person uses your assistance to get out of the chair but with inefficient movement or they drop your hand and get up on their own. A powered exoskeleton working without a direct link into the operator's nervous system has the same problem. It must work in parallel to what the human operator intends and without direct communication between the two. The powered exoskeleton should mimic and work with the human operator and appropriate time and apply joint torques/powers to assist the human with the chosen task (Figure 1). However, motor control of human locomotion is a complicated task and predicting how the human motor system regulates steady state walking has proven difficult with high error rates when a computer attempts to predict lower limb control. For example, active duty Military



Figure 1 - This powered exo-skeleton must integrate with the human operator to work in parallel with his movement while overcoming the mechanics imposed by the task and the environment. Problems with control can arise when the human operator applies forces on the exo-skeleton that conflict with what was expected by the controller. This error results in falls or sub-optimal movement.

personnel can easily exceed ten thousand of steps per day, therefore if a brain computer interface controller (BCI) linked to an exoskeletal system has even 0.5% error (Note: error rates of 1.2% are the current state of the art under laboratory conditions¹, that still means the Warfighter has the potential to fall 500 times per day. In a combat situation, this is a deadly situation. This task is further complicated when the motor system is subjected to a perturbation to steady state locomotion yet these perturbations are very common in the "real-world". Furthermore, BCI controllers need some sort of direct link into neural signals and this requires invasive surgery and finely tuned, delicate electronics that may not survive in the field. It may be better to have a powered exoskeleton that does not require direct access to the human operator's nervous system but instead is able to work in parallel with the human operator's intention. Therefore a basic understanding of the fundamental locomotor control principles is necessary to define how the normal human system is controlling locomotion because this knowledge then allows designers of

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powered exo-skeleton control systems to design control algorithm that would in tandem with the human system.

The Biomechanics and Motor Control Laboratory at Alabama State University is dedicated to the definition of fundamental principles of locomotor control. This is accomplished by systematically exposing the human to different controlled mechanical environments, measuring muscle outputs (electromyography), biomechanical outputs (joint motion, moments, forces, and powers) and then apply mathematical models to calculate the motion control strategy.

The installed GRAIL system is designed specifically to enable this type of research. GRAIL uses an instrumented dual-belt treadmill, a motion-capture system and synchronized Virtual Reality (VR) environments and electromyography (EMG). GRAIL supports gait and balance research, gait analysis and gait training by allowing the person to walk in challenging conditions. Real-time adjustments in GRAIL enable analysis and training during the same session.

The main components of a GRAIL are an advanced self-paced dual-belt instrumented treadmill mounted on a motion base, the GRAIL software, a visualization and audio system, a motion capture system, an integrated video system. This allows the researcher to rapidly change pitch and sway to perturb the subject or alter the visual flow to disorientate the person during gait or while standing to investigate balance.

Summary of the most important results



Figure 2 - The GRAIL system in operation.

The grant awarded to Alabama State University was focused on the acquisition and installation of a GRAIL system in the Biomechanics and Motor Control Laboratory. This was accomplished on July 27, 2015 (Figure 2). A timeline for the acquisition and installation was described in

detail in the interim report. This report will focus on what has been done since delivery of the GRAIL system and will be followed with plans for future research.

[A time lapse video of the GRAIL system's installation can be accessed here.](#)

[A video describing the GRAIL system's capabilities can be accessed here.](#)

Work using the GRAIL system has centered on:

- Troubleshooting problems with the forceplates
- Establishing a standard operating procedure using Motek's recommended methodologies
- Collecting pilot data for grant applications
- Collect data for student driven research projects
- Use the system for a problem based learning project for the Biomechanics course
- Optimizing the system to collaborate with other DoD centers
- Exposing larger audiences to the capabilities provided by the GRAIL system

Troubleshooting problems with the forceplates

After installation, the left forceplate experienced an intermittent problem where it would produce unrealistic force magnitudes and center of pressure. The intermittent nature of this problem made it difficult to solve. Eventually, Motek flew out a representative to investigate and a faulty ground was found inside the forceplate amplifier. The amplifier was repaired and the forceplates now appear to be operating normally.

Establishing a standard operating procedure using Motek's recommended methodologies

We have now standardized our data collection and reduction techniques. This was done using Motek's recommended markersets for defining joint centers and segmental motion. It uses Motek's Gait Off-line Analysis Tool to post-process data by excluding "bad" trials (e.g. right foot hit the left forceplate), time normalize the data to 100 datapoints, and then export to a .csv file. From there we use a custom written Matlab program to compile, graph, and organize for statistical analysis. We created a system operations manual describing all of these procedures.

Collecting pilot data for grant applications

We recently used the new GRAIL system to pilot an experiment that can investigate fundamental control principles of this step to step transition.

We collected pilot data on one person with intact limbs and one person with an amputation that was used in a NIH R15 grant application to identify the neuromechanical mechanisms that underlie gait asymmetries in people with uni-lateral transtibial limb loss during the step-to-step transition. This application scored well (impact score of 30) and we are awaiting news on if it was recommended for funding.

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We also used the same pilot data to demonstrate the GRAIL system's ability to perturbate gait in a small grant application to the American Orthotics and Prosthetics Association. That grant proposal will define the techniques used by the person with transfemoral amputation to prevent a stumble while using microprocessor controlled knee joints with different types of stumble recovery features.

Collect data for student driven research projects

The GRAIL system was used to collect data on three student driven projects that involve human integration with orthotic and prosthetic devices.

The first student driven project was to evaluate the performance of a stance control orthosis on the gait of someone with a low level spinal cord injury (Figure 3). Stance control orthoses are non-powered, mechanically controlled exo-skeletons that cross the ankle and the knee joint. The knee joint has a clutch mechanism that locks during stance phase and then unlocks to allow the person to flex the knee for limb clearance during swing. This work utilized the GRAIL to collect data on gait speed, limb movements, and joint moments to understand how the person interacted with the device for locomotion. Although the focus of this project was for the students to understand how best to design an orthotic treatment for a person with spinal cord injury, the information gained can also inform powered exo-skeleton design because it provided a simpler model to understand human/device integration. This work was presented as a poster presentation at the American Academy of Orthotists and Prosthetists annual meeting this past February in Orlando, FL.²

[A video of this data collection can be accessed here.](#)

The second student driven project was to develop a prosthesis emulator that can be applied to people that do not have an amputation (Figure 4). This emulator was designed to replicate the biomechanics of the residual limb/prosthetic socket interface as if the person had a transtibial amputation and could be used to understand differences in lower limb control related to that interface. This model has several applications to address larger questions on how humans interface and control passive exoskeletons that could also be used to improve passive and powered exoskeleton systems. This work was presented as a poster presentation at the American Academy of Orthotists and Prosthetists annual meeting this past February in Orlando, FL.³



Figure 3 - Data collection for a student driven project to develop a stance control orthosis for a person with spinal cord injury.



Figure 4 - Another student project used the GRAIL to test prosthesis emulators they developed.

A third student driven project was to investigate the clinical assumption that there is a connection between symmetrical limb movement and symmetrical joint loading in people with amputation. The GRAIL provided a method to create symmetrical movement in people that walk asymmetrically by speeding up the belt on the amputated side while recording ground reaction forces and joint moments. These students found that when step length and joint movement symmetry were created by speeding up the belt on the amputated side, this led to an increase in limb loading asymmetries (Figure 5). This demonstrates the significance of how the current clinical paradigm to encourage symmetry may lead to unintended consequences, like increased sound limb loading.⁴

Use the system for a problem based learning project for the Biomechanics course

The biomechanics course at Alabama State University is an interdisciplinary course that combines students in the MS in Prosthetics and Orthotics program and students in the doctorate in Physical Therapy program. The GRAIL system was used extensively throughout the course to demonstrate how different aspects of how people walk and for a problem based learning project that mimics a small scale research project (Figure 6). The students develop a hypothesis about how someone's gait would respond to a perturbation (e.g. uphill, downhill, unequal leg length, high heels, etc.). The hypotheses must be specific and include a biomechanical mechanism that would support why they would expect this to happen. The class then collects data on one subject using the GRAIL system. The system's ability to quickly collect and reduce data was leveraged to provide the students spreadsheets of

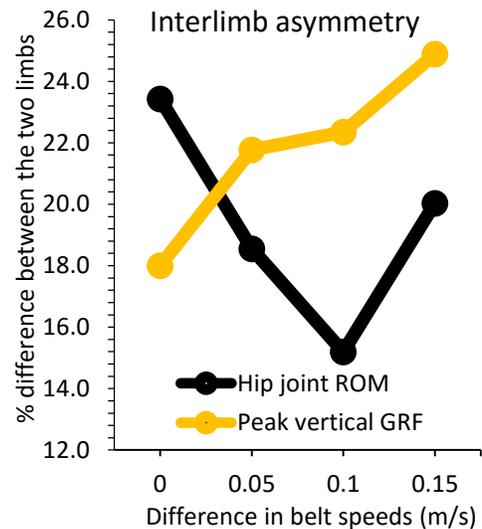


Figure 5 - Data from one person with amputation where the belt speed on the amputated limb was increased. This minimized kinematic differences between limbs (hip joint range of motion, black line, is shown here is representative of all kinematic measures taken) but created greater differences in limb loading (yellow line).

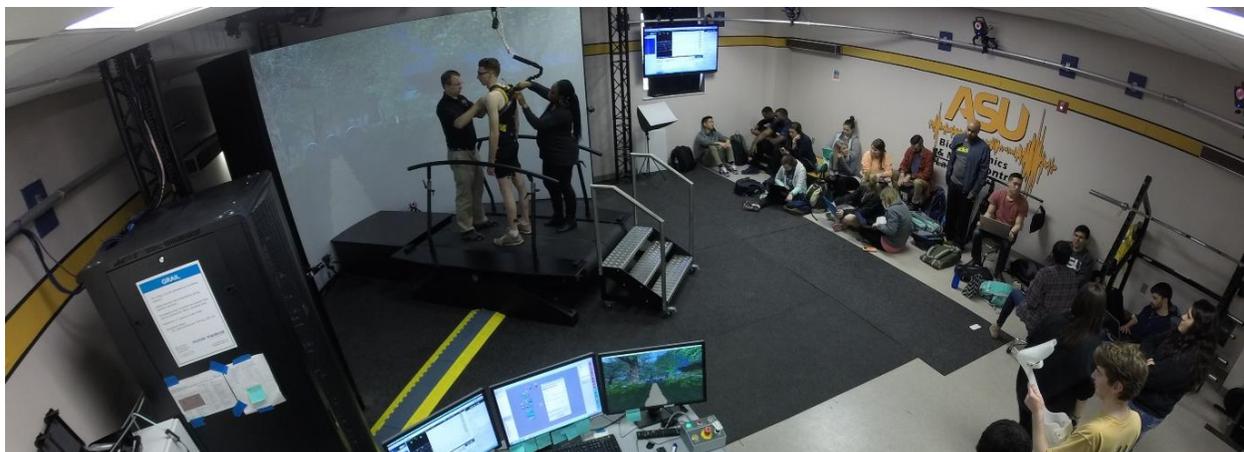


Figure 6 - Student in the Biomechanics course used the GRAIL for test hypotheses they developed about how people walk.

data ready for statistical analysis. The students then pulled out relevant measures from the data collected to test and address their hypotheses. The students then present their findings to the class. This project was successful and will continue to be used as a hands on learning experience for our students in the future.

[A time lapse video of this project can be accessed here.](#)

Optimizing the system to collaborate with other DoD centers

The Extremity Trauma and Amputation Center of Excellence is a DoD/VA collaboration mandated by Congress to conduct research focused on the mitigation, treatment and rehabilitation of traumatic extremity injuries and amputations. The center comprises of DoD laboratories at Walter Reed National Military Medical Center, Center for the Intrepid at Brooke Army Medical Center, and the Naval Medical Center San Diego. Research conducted at the Center for the Intrepid at Brooke Army Medical Center is directed by Dr. Jason Wilken and they use a similar Motek system (CAREN). Dr. Wilken has given us all of their standard operating procedures on how they collect and reduce data. This process is different than the procedures incorporated by Motek because the DoD centers use a different markerset that is more versatile. The DoD centers utilize a software program called Visual3D to process raw data. Therefore, the DoD center's standard operating procedures require the use of Visual3D. We purchased a copy of Visual3D with funds from the grant and we are now in the process of integrating that with the system and the DoD standard operating procedures so that we can easily collaborate with these centers for future research studies.

Exposing larger audiences to the capabilities provided by the GRAIL system

The GRAIL system increases the research infrastructure at Alabama State University and this increase in infrastructure has led to many Media outlets showing our laboratory to a larger audience. The GRAIL system has been featured on local news, the front page of the newspaper (Figure 7), and a magazine dedicated to prosthetics and orthotics.⁵⁻⁷



Figure 7 - The GRAIL system was used to expose larger audiences to how this increase in research infrastructure will benefit those that depend on optimization of a human with a machine.

Summary

Funds were provided through this funding mechanism to acquire and install a Motek GRAIL system at Alabama State in order to advance DoD research interests, advance research capabilities at a Historically Black College or University (HBCU), and advance research education. The GRAIL system will continue to advance DoD research interests through investigating fundamentals of locomotor control that can be applied to human/machine integration. This has been demonstrated by the collection of pilot data on interlimb neural

control of the step-to-step transition that was used for a NIH R15 grant application. More detail on those data can be found in our 6 month interim report. The GRAIL system has advanced research capabilities at a HBCU in its unique ability to perturb gait and rapidly collect and process gait data. This has enabled research to be conducted in ways not previously possible with our overground walkway setup. We can collect five times more trials in one fifth the time of our previous setup. The GRAIL system has advanced research education by enabling the problem based learning projects during the biomechanics class and enabling students to use this equipment to conduct their own research projects.

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