National Aeronautics and Space Administration

Plugin for Integrated Exoskeleton Simulations (PIES)

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EXECUTIVE SUMMARY

Upper extremity offload is a new capability to be developed for the Active Response Gravity Offload System (ARGOS) at the Johnson Space Center. To address the need, the Actuated Real-time Control for ARGOS Negation of Gravitational Effects on the Limbs (ARC-ANGEL) system is being designed and developed by the HumanWorks team in the Flight Systems Branch (ER3).

The Plugin for Integrated Exoskeleton Simulations (PIES) is a multibody modeling and analysis capability developed by the Digital Astronaut Simulation (DAS) team in the Simulation and Graphics Branch (ER7). The C++ plugin is used in the open source biomechanics software, OpenSim (Stanford University), and integrates human multibody modeling with system dynamic modeling. The latest 'flavor' is the ANGEL with Passive and Powered Line of force Evaluation (APPLE) PIES.

INNOVATION

APPLE PIES enables:

- Quantification of offload forces and the impact of a given ANGEL design on human shoulder torques,
- Design requirements development based on recorded human kinematic data (e.g., arm range of motion or EVA tasks) and the corresponding system performance to achieve simulated lunar shoulder torques,
- Evaluation of new system configurations in simulation, before or as a supplement to manufacturing prototypes and human-in-the-loop data collections,
- Design iteration based on analysis findings.

COLLABORATION

Through the leadership of Christopher Beck/ER3, the HumanWorks hardware design team provided motivation and direction in the development of APPLE PIES, and all data collections with the DAS team were a joint effort. Collaboration with HumanWorks interns enhanced data sharing and progress of simulation efforts during the project (a special thanks to Clarissa Rincon for direct assistance in analysis preparations). Our DAS team members Fouad Matari and Charlotte Bell were instrumental in developing theoretically scaled models based on standards (such as NASA-STD-3001 and xPGS end item specifications) and obtaining arm kinematic trajectories which were used to assess maximum and minimum drivers for ARC-ANGEL design requirements.

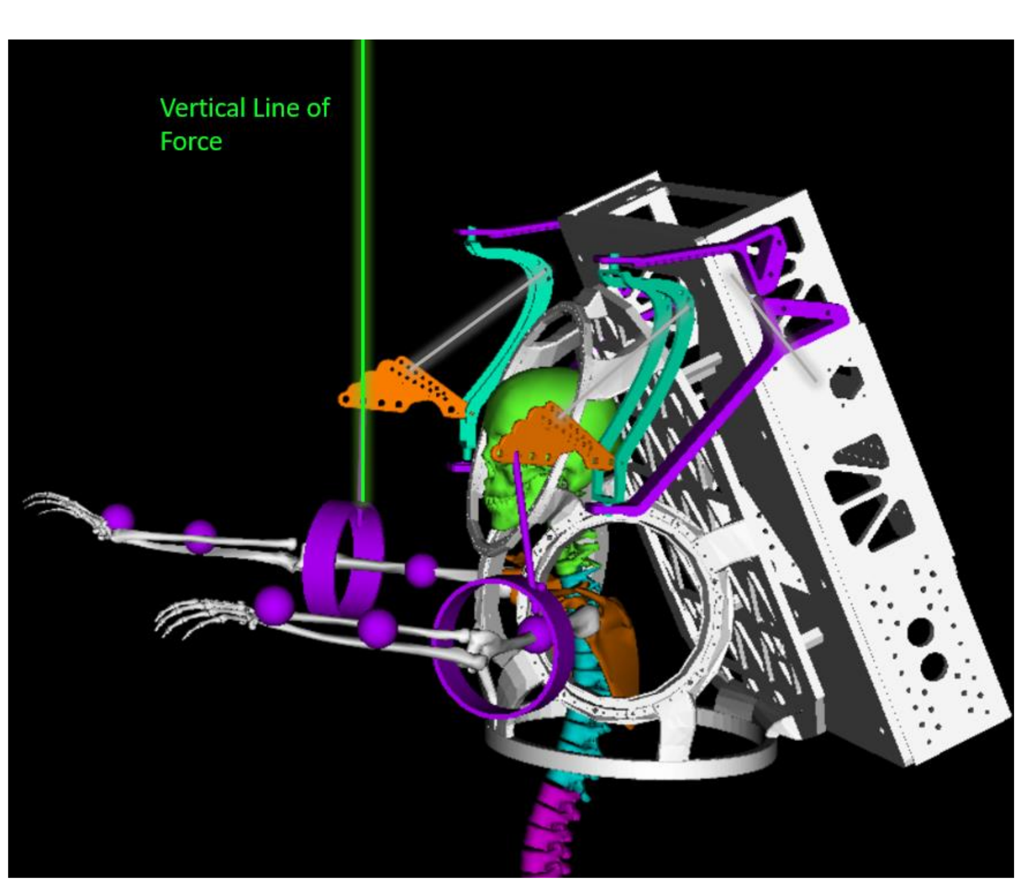

Figure 1. OpenSim model with vertical line of force indicating "Ideal Offload" vector assessed for a particular cuff location. ANGEL component geometry used in Passive and Actuated prototypes is also incorporated in APPLE PIES.

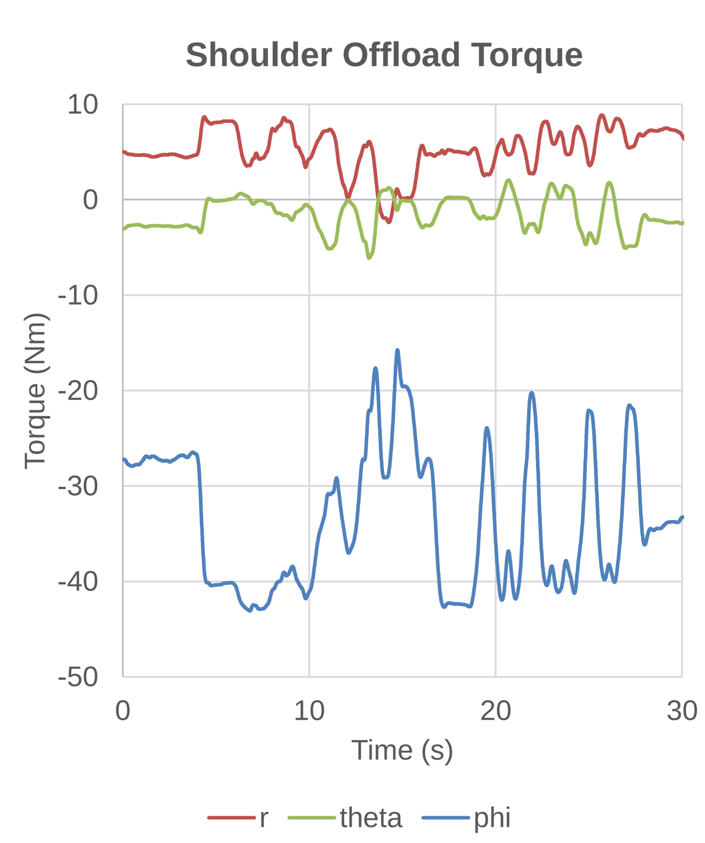

Figure 2. Shoulder torque required to be offloaded for lunar representation, based on a Range of Motion task performed with the MK-III in ARGOS which was scaled to a Theoretical Maximum subject.

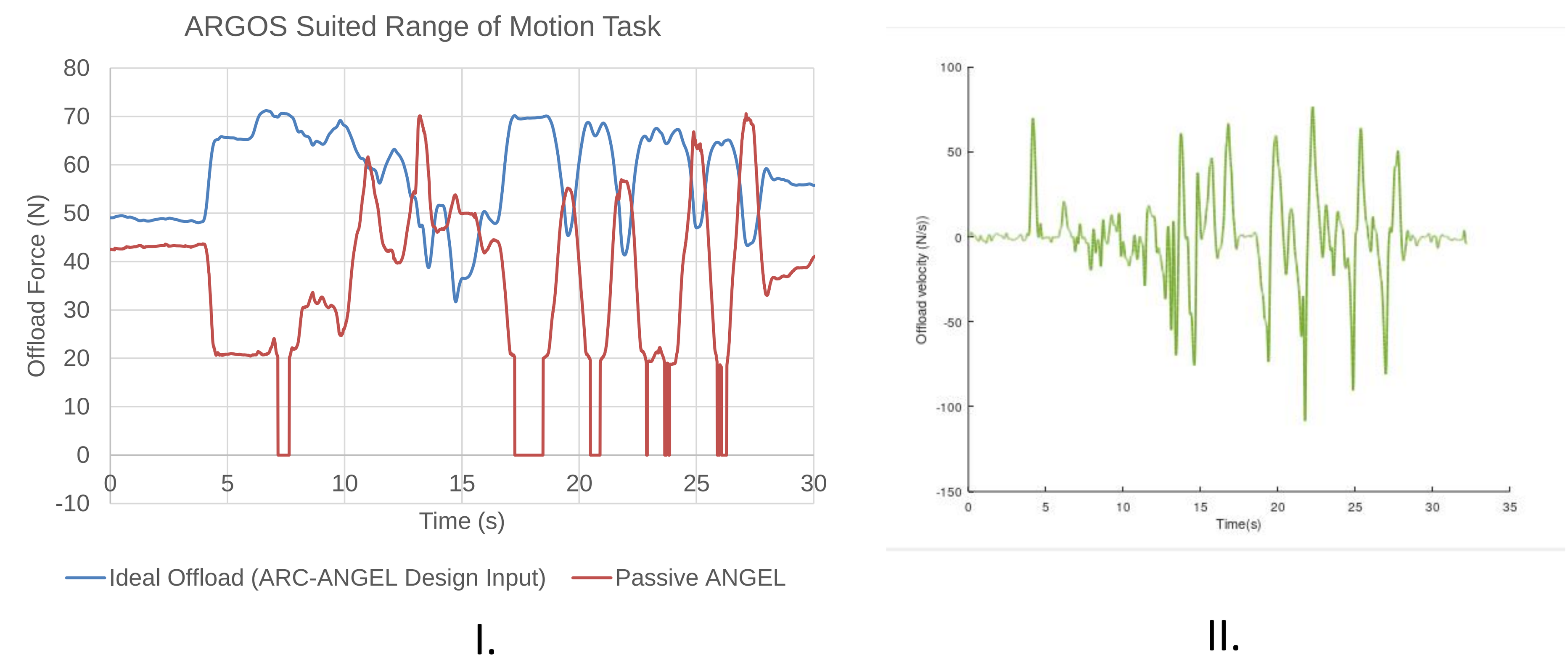

Figure 3. Examples of analytical findings used to inform ARC-ANGEL design requirements (I. Vertical offload force required to achieve lunar shoulder torque for the ARGOS test subject, compared with the offload provided for a passive ANGEL design; II. Offload force rate of change to inform motor control and control system requirements based on the Theoretical Maximum scaled subject)

OUTCOMES & INFUSION

Beginning in FY20, the DAS analyses helped inform early passive ANGEL design topology and then characterized passive ANGEL prototypes from human-in-the-loop motion capture data collections, with a hard upper torso mockup/test stand in the Prototype Immersive Technology (PIT) lab and the MK-III spacesuit in ARGOS. Analysis results highlighted the 'goldilocks zone' trade of aligning with lunar or Martian shoulder torques only for certain ranges of arm motion, and the reduced vertical offload when the crew member bends forward.

In support of ARC-ANGEL design requirements development and early design considerations such as motor selection, an analysis was performed to determine the offload needed to achieve lunar representative shoulder torques. This was completed first for the "ideal case" (pure vertical offload).

The following outcomes were assessed (see Figure 3):

1. Offload force
2. Offload force rate of change
3. Cable length rate of change

Highlighted findings included upper arm angles where an offload force singularity would occur and also the impact of forearm orientation on offload (in consideration of sensor measurement requirements for upper arm and elbow angles).

Throughout ANGEL development, the DAS team formulated a method and added capability to PIES for calculating passive ANGEL device angles based on human motion alone, using a static equilibrium condition considering device geometry/behavior and spring length minimization. In one FY23 ARC-ANGEL design, where component geometry is maintained but the passive spring is replaced with the motor-actuated cable, the principles can be again leveraged to estimate device angles as well as cable force required at attach points.

FUTURE WORK

Future work may include assessing alternative design concepts and further informing ARC-ANGEL software development such as in trades between assumptions and measurements for test subject anthropometry, body tracking, EVA tool use, etc. in the representativeness of the offload provided. The DAS team also aims to rearchitect PIES for ease of extensibility to other types of ANGEL designs and externally worn systems.

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