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USING INERTIAL MEASUREMENT UNITS FOR MEASURING SPACESUIT MOBILITY AND WORK ENVELOPE CAPABILITY FOR INTRAVEHICULAR AND EXTRAVEHICULAR ACTIVITIES

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Human spaceflight destinations are expanding to include a multitude of environments that will offer different mobility challenges to explorers due to varying gravity levels and surface operations. Intravehicular Activities (IVA) suits might include a basic "get-me-down" suit for suborbital spaceflight, or a high performance pressurized pilot suit where arm mobility and field of vision are particularly important. Future Extravehicular Activities (EVA) will likely accommodate various spacesuit architectures including: a microgravity station/craft maintenance suit where hand dexterity is critical; a close proximity operation suit for asteroid missions where manoeuvrability and visibility are critical; and a planetary surface suit for the Moon or Mars where leg mobility is a key requirement. Spacesuit kinematics are currently measured using video motion capture or photographic analysis systems. Although these methods measure the external motion of the suit, they do not capture the physical body motions within the suit and in the case of motion capture, they are restricted to a laboratory setting with significant overhead for camera calibration and set-up. Inertial Measurement Units (IMUs) use accelerometers and gyroscopes to estimate relative translation and rotation. IMU systems are mobile, low-powered, and offer an economical and efficient kinematic tracking capability for use in a laboratory or in the field. In this study, we applied IMU sensors to study space-suited motion. To first validate the use of IMUs for motion tracking, we tracked knee flexion angle while walking using both IMUs and a Vicon motion-capture system, which is considered the industry gold standard for kinematic analysis. The IMU knee joint angle average root-mean-square error with respect to the Vicon system was 5.4 ± 2.4˚, demonstrating the potential of the new system. We then used the IMUs, in conjunction with a Contingency Hypobaric Astronaut Protective Suit (CHAPS), to measure elbow flexion/extension, shoulder flexion/extension, and shoulder abduction/adduction motions for unsuited, suited and unpressurized, and suited and pressurized conditions. Results from the elbow study demonstrate our ability to capture joint angles in a laboratory environment with the goal of being used in any environment. In general, the internal IMU angle on the subject's body was approximately 25˚ larger than the external CHAPS IMU external angle measured. A brief discussion summarizes key findings and identifies limitations in the test configuration. Recommendations for future implementation and testing are outlined, and conclusions are drawn on the usability of IMUs to investigate astronaut mobility and to provide work envelope results.

I. INTRODUCTION

The new human spaceflight market in suborbital space tourism and research flights as well as new crew capabilities to the International Space Station (ISS) will mix customer needs with high-powered vehicles that lack extensive flight history. It is important to monitor passenger comfort and safety and inform future improvements to mission elements such as spacesuits, personal cabin space, and throttling profiles. The fast pace of commercial orbital vehicle development will benefit from novel mobility measurement techniques, especially if they can be taken within the vehicles during operational development. Inertial measurement units (IMUs), sensors that integrate data from orthogonal gyroscopes, accelerometers, and magnetometers, can aid in these assessments.

The goal of this research is to develop novel applications for IMU technology in characterization of human motion, such as estimating orientation, acceleration, velocity, and position during restrained or natural movement. In particular, this work focuses on spacesuit mobility and how IMU data can be used to construct range of motion joint angles and eventually work envelope definitions in a realistic test environment. This data can aid in the development of future space suits and improve knowledge of current suit performance and limitations.

Systems of inertial sensors may also have many terrestrial applications where enhanced monitoring of human movement is beneficial. These areas include estimation of ambulatory joint kinematics[1-4], injury rehabilitation[5,6], assessment of neurological movement disorders[7], and enhancement of athletic performance[8,9].

II. SPACESUIT MOBILITY TESTING BACKGROUND

Pressure suits are worn by pilots and astronauts to protect them from a variety of hazards including low-pressure environments and thermal extremes. Pressure suits worn inside the vehicle during dynamic phases of flight, such as launch, entry, and docking are primarily designed to protect the crewmember in the event of an emergency. During nominal unpressurized operations, the crewmember must be comfortable and have the mobility to perform mission tasks, such as ingressing the vehicle and performing flight operations. During an emergency, the suit must enable the crewmember to perform any operations necessary to return to safety while protecting the crewmember from hazards. To that end, launch and entry suits often incorporate bailout systems, fire protection, cold-water immersion protection and integrated flotation, which are all dependent on the requirements and interfaces of the vehicle[10]. The current set of requirements outlined by NASA for commercial vehicles is in the ISS Crew Transportation and Services Requirements Document CCT-REQ-1130. It does not specifically mandate a pressure suit, but the NASA Astronaut Office considers it mandatory[11].

Similarly, pressure suits for the emerging commercial spaceflight industry will be primarily worn unpressurized, but in the event of an emergency, the suit must ensure the crewmember survives and, if necessary, can continue to perform the necessary functions to return to safety. It is important to note though that pressure suit needs vary amongst the different mission profiles, as differing levels of mobility will be required of passengers in different vehicles. Even within a single vehicle, the mobility requirements are varied, as pilots must be able to continue to the fly the spacecraft while pressurized (in the event of a cabin depressurization), while suits for passengers must simply ensure their survival.

Understanding and quantifying exactly how much mobility a crewmember needs to perform each task is critical to derive requirements that will not over constrain the design. It is important to recognize that increases in pressurized mobility often come at a cost, such as a mass penalty, detriment to unpressurized comfort, or increased development costs[11,12]. The mobility requirements therefore must not drive a design beyond that which is absolutely necessary, as other desirable characteristics of the suit may be sacrificed.

Additionally, as NASA prepares for exploration missions outside of low earth orbit, it is increasingly important to be able to quantify, communicate, and validate, space suit mobility for suits worn outside the spacecraft. These suits are always worn pressurized, and as such pressurized mobility becomes far more critical. One of the long term goals of space suit design is to design suits that approach as close as possible to "shirt-sleeve mobility", such that an astronaut in a pressurized space suit could perform all the same tasks, with the same ease, as a geologist on earth in a t-shirt and shorts. Research at MIT in the Man-Vehicle Laboratory (MVL) has been moving towards this mobility goal with incremental subsystem design of a mechanical counterpressure BioSuit™ [13]. In order to achieve this goal, the mobility enabled by various joint designs must be well understood and quantified. Improvements to the joints can then in turn be quantified, by measuring the reduction in mobility, and understanding the physical principles responsible for the reduction. Without continuous benchmarking and iteration, the suit designer cannot make progress towards a highly mobile joint.

It is evident then that proper characterization of mobility requirements – how much mobility is needed to perform all mission tasks – as well as mobility capabilities – how much mobility a certain space suit enables – is absolutely essential for both government space programs and the commercial spaceflight industry.

Spacesuit Environments: IVA and EVA

There are essentially two key working environments that must be considered for suit mobility design. Intravehicular Activities (IVA) suits might include a basic "get-me-down" suit for suborbital spaceflight, or a high performance pressurized pilot suit where arm mobility and field of vision are particularly important. Future Extravehicular Activities (EVA) will likely accommodate various spacesuit architectures including: a microgravity station/craft maintenance suit where hand dexterity is critical; a close proximity operation suit for asteroid missions where manoeuvrability and visibility are critical; and a planetary surface suit for the Moon or Mars where leg mobility is a key requirement.

Mobility Methodologies

Several methodologies have been used to measure mobility, though two methods have emerged as the most common within the spacesuit community[14]. Unfortunately each has its drawbacks. Photogrammetry, the process of measuring joint angles from pictures of a subject in the suit at the extremes of a joint's range, has been used to quantify pressure suit mobility dating back at least to the Apollo program[15], and through various space suit development programs[16,17] including the most recent prototype suits developed for NASA's project Constellation[12,18,19]. This method only quantifies isolated joint movements, making it difficult to properly characterize the suit's mobility for complex tasks. Additionally, this method requires the subject to hold a joint at "maximum" angles, which can be very workload intensive, and as a result tends to underestimate a suit's full range of mobility.

The second method commonly used, developed more recently with advances in technology, involves three dimensional video motion capture technology. Subjects in suits are outfitted with reflective markers, and systems of multiple cameras are used to track the markers as the subject performs various functional tasks. The coordinates of the markers can be used to measure individual joint angles using inverse kinematics software. This method was used extensively for the derivation of requirements for project Constellation[20]. Motion capture methodology is advantageous as it captures mobility during functional movements and tasks, but it is costly both in terms of equipment needed and in post-processing time. Additionally, it requires line of sight for several (2-3 minimum) cameras on each marker at all times, restricting it to a laboratory environment and making it difficult to track motions within a mock-up. This drawback was at least partially alleviated in a 2011 study through the use of a somewhat transparent mock-up of the Orion vehicle[21,22]. The mock-up allowed the cameras to see "through" the vehicle, and motions could be tracked as subjects performed all the mission tasks, such as ingressing/egressing the vehicle, attaching the harnesses and umbilical, and other tasks. The mock-up was an innovative solution to the problems associated with motion capture using reflective markers and cameras, however it demonstrated the need for the ability to capture mobility data in non-laboratory environments, as it would have been ideal to use a higher fidelity mock-up of Orion.

Recently, a new method of implementing IMUs has become feasible, which has the potential to enable mobility characterization during functional tasks in all environments, without the need for line of sight from expensive camera systems. Two initial studies have recently been performed[23,24] demonstrating the potential for this methodology, which involves placing small inertial measurement units (IMUs) onto the subject. These trials have shown that data from the IMUs can be converted into joint angle measurements as a subject performs various tasks in various environments. This methodology enables mobility measurement outside the laboratory environment, captures motion data in three dimensions during functional tasks, and eliminates the need for additional vehicle mock-ups.

Inertial Measurement Units (IMUs)

In order to understand the motion of the human body within a relevant environment (spacecraft habitable area or spacesuit), IMUs are selected to demonstrate a novel way of collecting data. IMUs use accelerometers and gyroscopes to estimate relative translation and rotation. Desirable IMU characteristics include:

- Sized to fit application (minimal mass or specific shape);
- Low power consumption / long battery life;
- Dynamic range, resolution, bandwidth, Sampling Rate, Noise, Sensitivity;
- Connection to other recording infrastructure versus data logging / standalone;
- Comfort and/or unobtrusiveness;
- Long-term monitoring; and
- Affordable price.

This research effort has evolved from a lineage of projects at MIT's MVL. In order to compare the use of IMUs for estimation of lower limb joint angles against the standard motion capture methodology and inverse kinematics software, a study was conducted using commercial IMUs to capture three-dimensional acceleration and angular velocity data generated during human walking. Preliminary results using an extended Kalman filter to estimate both knee and ankle joint angles were encouraging[3]. Collaborators at MIT and the Instituto Superior Técnico (Portugal) demonstrated the efficacy of IMUs as sensory systems for gait analysis replacing the standard motion capture camera method. Through the use of different processing tools and custom filtering, it was possible to improve the data provided by the IMUs to be used for prosthetic and orthotic devices to estimate joint kinematics during walking[25,26]. On-going research implements IMU joint kinematics in real-time for the design of ankle-foot smart orthotics[27,28].

For an array of experimental medical and space applications, the authors have selected IMUs that include a set of three magnetometers, gyroscopes, and accelerometers each. These IMUs (Opals™, APDM, Portland, OR) are low mass wristwatch-sized devices enabled by real-time wireless data capture or storage for later download (see Fig. 1).

To assess IMU capabilities for human spaceflight applications, a pilot study was conducted in a car on a relatively smooth highway looking at constant velocity motion and acceleration profiles. The aims of the study were to examine ideal IMU positions and operational protocol for data collection using a car and seat interface as an analogue to suborbital spaceflight keystone events simulating a seated launch[23]. Preliminary results indicated that IMUs can be used to characterize the human body's motion in an analogue situation and the vehicle's vibrational environment.

Fig. 1: APDM IMUs are small wearable devices. Axes are shown for IMU body reference frame.

III. PRELIMINARY VALIDATION OF IMUS VS. MOTION CAPTURE GOLD STANDARD

To validate this data collection method we tested the accuracy of the APDM IMUs during normal walking. The IMUs were compared to the "gold standard" of kinematic data collection, the Vicon motion capture system in the Wyss Institute's motion capture laboratory. This system uses an array of eight T-series cameras to track reflective markers illuminated by infrared light.

IMUs were strapped to the subject's legs and a plaque labelled with reflective markers was attached (Fig. 2).

The locations of the reflective markers aligned with the Y and X axis of the IMU and enabled the 8-camera Vicon motion capture system in interpret the rotation of the IMUs strapped to the lateral side of the upper and lower leg. The subject was instructed to walk the length of the motion capture volume. Limb segment rotation in the sagittal plane was recorded with the Vicon and APDM IMU system. Knee rotation was determined by subtracting the rotation of the lower leg from the reference rotation of the upper leg. A representative trial is shown in Fig. 3.

Fig. 2: IMU placement and reflective marker locations.

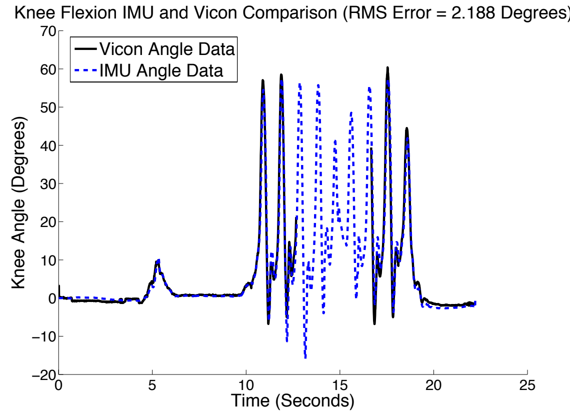

Fig. 3: IMU-Vicon Knee walking comparison.

Areas in Fig. 3 where the Vicon data disappears from the plot is where the subject stepped outside the collection volume. Data was collected for 13 trials. The average RMS error (relative to the Vicon system) throughout the samples was 5.4 degrees with a standard deviation of 2.4 degrees. This analysis shows that the IMUs can be used as a substitute for a Vicon motion capture system when an optical system is unavailable. It also demonstrates potential advantages of the IMU approach: freedom of movement without the restriction of a specific motion capture volume.

El-Gohary et al. (2011)[29] investigated the use of APDM IMUs for estimating joint angles of a multi-segment limb using a custom unscented Kalman filter algorithms and compared data to an optical tracking system (Eagle Analog System, Norwood, MA). All elbow and shoulder motions analysed were found to have IMU data correlate with greater than 0.9 to the motion tracking system, and all cases were statistically significant for both normal (rate not specified) and fast (as fast as user could bend elbow) speed motions.

Another study found the APDM IMU system to have a high Pearson's R correlation while compared to a Vicon system ($R > 0.90$) for gait cadence, head rate of rotation, and torso rate of rotation. These measurements are typically used to test patients with mild traumatic brain injury[30].

IV. CHAPS MEASUREMENT METHODOLOGY

Testing at David Clark Company

The APDM IMU system was brought to the David Clark Company (Worchester, MA) to test basic mobility in the Contingency Hypobaric Astronaut Protective Suit (CHAPS). Before testing, it was decided to focus on the elbow joint motion. The motion of the entire arm could potentially be used to generate a point cloud of tracking data to generate a work envelope, which is further explored in the recommendations in section VII.

IMUs were placed on the forearm and bicep both directly on the subject's body and on the external surface of the CHAPS (two external IMUs are indicated on Fig. 4 on the CHAPS). Additional IMUs were placed on the fingertips (outside of glove) and on a fixed position on the wall. Three sets of motion were recorded including: elbow flexion/extension; shoulder flexion/extension; and shoulder abduction/adduction. The IMUs were used to data log the motion for both scenarios of the suit unpressurized and with the suit pressurized to 1 psig. Two different methods were examined for conducting the motion. The first method had the subject tap the fixed wall IMU before each arm motion (tap), and the second method had the subject move in a continuous motion (continuous). For every trial, three complete arm motions were conducted and the trials were repeated twice for all sixteen scenarios (the two methods were only used for the elbow motion).

The elbow starting position of a straight arm (locked) of 0˚ was used in every elbow trial (see Fig. 4 "zero angle"). Flexion, or elbow bend, was considered positive rotation according to the Standardization and Terminology Committee of the International Society of Biomechanics[31].

A similar study at the University of Maryland Space Systems Laboratory[24], investigated outfitting IMUs internal to a spacesuit, using the CHAPS as a demonstration of the technology. The Body Pose Measurement System (BPMS) uses 18 IMUs on a conformal garment worn under the suit to track body motion by measuring the attitude of the major long bones.

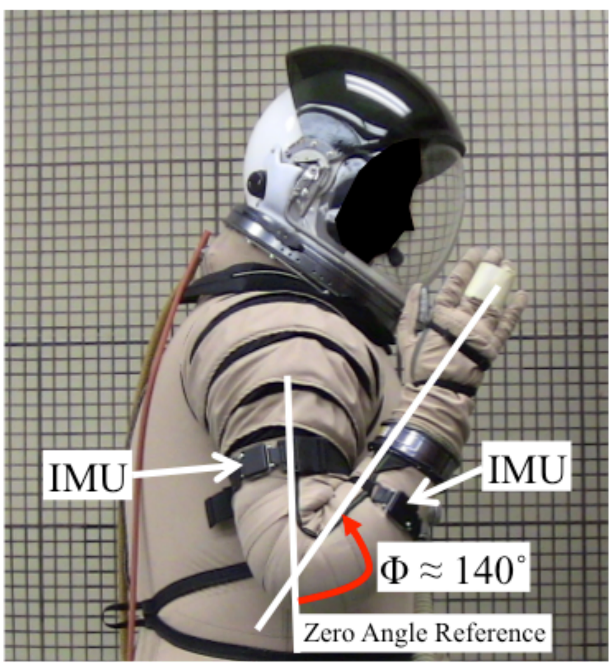

Fig. 4: IMU Placement on CHAPS with elbow flexion measurement (used with Permission from David Clark Company).

Results: Euler Angle Calculations

The following is an overview of the code developed in MATLAB (The Mathworks, Natick, MA) to reduce the acquired IMU data and find the final three Euler angles for a pair of IMUs about a given body joint. The basic approach is to calculate a rotation matrix that transforms one IMU frame into another IMU frame, and then determine the Euler angles for that rotation matrix, which represent the 3dof rotations of the joint between the two IMU frames. In more detail, the approach is:

1. Import data from IMU csv file to Matlab
2. Convert Quaternions to Euler Angles using Matlab's "quat2angle" (Aerospace tool box)
   - Angles are in body reference frame X, Y, Z with respect to North, West, Up (NWU) world frame that the IMUs use.
3. Generate rotation matrices for both IMUs in joint angle couple, from Bong Wie Equation 5.13 on 311[32]:

$$R^{B/A} \equiv R_1(\theta_1) R_2(\theta_2) R_3(\theta_3)$$

$$= \begin{bmatrix} c_2 c_3 & c_2 s_3 & -s_2 \\ s_1 s_2 c_3 - c_1 s_3 & s_1 s_2 s_3 + c_1 c_3 & s_1 c_2 \\ c_1 s_2 c_3 + s_1 s_3 & c_1 s_2 s_3 - s_1 c_3 & c_1 c_2 \end{bmatrix}$$

   where,
   $R^{B/A}$ is the rotation matrix to B (NWU frame) from A (body frame of individual IMU – A1 and A2 are used in this paper to illustrate the two matrices for a joint angle couple as described below)
   R_i are rotation matrices about Euler angles θ_1, θ_2, and θ_3 that are not shown in this summary.
   $c_i = \cos\theta_i$
   $s_i = \sin\theta_i$
4. Rotate the first IMU to NWU frame and then to second IMU body reference frame using two rotation matrices. This is done by the following matrix chain-rule multiplication of the transpose (inverse) of IMU-A1:

$$R^{B/A1} = \text{ rotation matrix from A1 to NWU}$$

$$R^{B/A2} = \text{ rotation matrix from A2 to NWU}$$

$$R^{A1/A2} = R^{B/A2}\left(R^{B/A1}\right)^{-1}$$

5. Compute the final three Euler angles from the double rotation ($R^{A1/A2}$) using methodology such as G.G. Slabaugh's white paper[33]. The pseudo code to

find both possible solutions* for each angle is as follows[33]:

```
if (R31 ≠ ±1)
  θ1 = −asin(R31)
  θ2 = π − θ1
  ψ1 = atan2(R32/cos θ1, R33/cos θ1)
  ψ2 = atan2(R32/cos θ2, R33/cos θ2)
  φ1 = atan2(R21/cos θ1, R11/cos θ1)
  φ2 = atan2(R21/cos θ2, R11/cos θ2)
else
  φ = anything; can set to 0
  if (R31 = −1)
    θ = π/2
    ψ = φ + atan2(R12, R13)
  else
    θ = −π/2
    ψ = −φ + atan2(−R12, −R13)
  end if
end if
```

where,
θ_1, ψ_1, Φ_1 and θ_2, ψ_2, Φ_2 are the two Euler angle solutions for the double rotation
$R_{i,j}$ is the element in the *ith* row and *jth* column of the 9x9 $R^{A1/A2}$ matrix.

6. Data may jump from π to –π in the solution space so "unwrap" is recommended in Matlab.
7. Zero the starting point if necessary for given joint angle set.
8. Plot rotation about primary axis (in the case of the elbow, this was the Z axis of the IMU body frame or Φ from the double rotation to A2 reference frame).

V. RESULTS: CHAPS ELBOW JOINT ANGLE

The data from the four IMUs measuring the elbow flexion inside the suit on the body and on the outside of the CHAPS were calculated and the final z-axis Euler angle was analysed for trends. A typical output plot is shown in Fig. 5 that shows the internal angles of the elbow flexion with larger values than the CHAPS. This sample plot is from the elbow in continuous motion with the CHAPS pressurized to 1 psig. Fig. 6 is a cross-sectional rendering of the CHAPS and human subject, which was developed to visually demonstrate the angular differences.

*There are two solutions because of properties where sin(π - θ) = sin(θ) and cos(θ) ≠ 0. Slabaugh explains how to handle these in his paper.

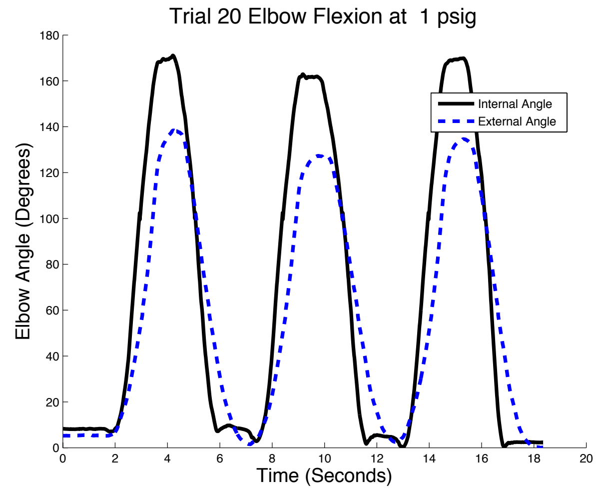

Fig. 5: Elbow flexion data showing internal angle of subject's motion larger than motion of the CHAPS.

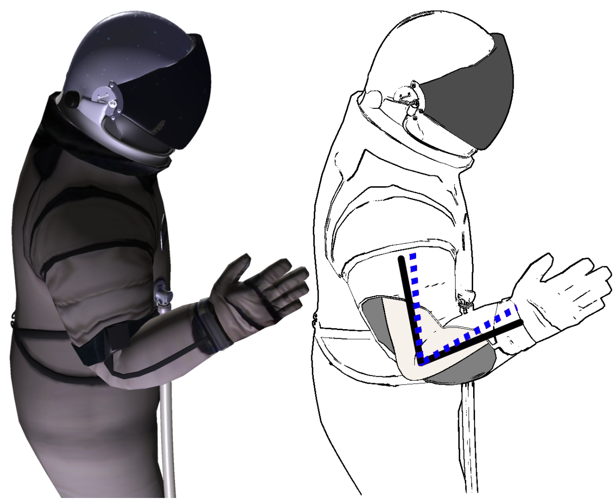

Fig. 6: Rendering of the CHAPS and human user showing approximate differences in elbow joint values.

Assuming the arm started in a perfectly straight position before every elbow flexion, the peak-to-valley difference was measured for both internal (on the subject's body) and external (on the CHAPS) angles. These maximum movement values were subtracted to find a final difference value. Video data was also used to compare the CHAPS external data and was found to be similar within a few degrees (see Fig. 1 for snapshots of elbow straight and fully bent under 1 psig conditions from video). Video was not shot of all trials so it was not statistically analysed. The CHAPS maximum angle lags the internal body, but these values were not investigated in this study.

Table 1 summarizes the statistical tests that compared the different methodologies and suit pressure results. If a scenario has a P value of less than 5% it is considered significant (* denotes value is significant), meaning that the data closely match. For example, it was found from the measurement of the internal angle, that the two methodologies of tap versus continuous yielded similar results (P=0.005) and that the measurements were similar regardless of the CHAPS pressure (P=0.002). This was not true for the external angle, as the results of the methodology differed enough to be not significant (P=0.128). However, the final values of angle differences were found to be similar regardless of method (P=0.000), but dependent on suit pressure (P=0.349).

Table 1: Statistical P-Values calculated to investigate spacesuit pressure and test methodology significance

	Method (Tap/Continuous)	Suit Pressure (0/1 psig)
Internal Body Angle	0.005**	0.002**
External Suit Angle	0.128	0.001**
Difference of Angles	0.000**	0.349

**Significant value

To distinguish some of the calculated averages of all of these cases, values are presented in Table 2. Since the method for the final angle data is significant (not much difference between two methods) we can look at final results and standard deviations by averaging all of the unpressurized (26.2 ± 6.7˚) versus pressurized values (24.2 ± 7.1˚). We see that the pressurization of the suit leads to slightly reduced angle values of the overall elbow flexion. The final results also show a different story, that the continuous motion led to bigger angle differences regardless of pressure.

Table 2: Peak angles calculated to investigate spacesuit pressure and test methodology significance

	Internal Body Angle (˚)	External Suit Angle (˚)	Difference of Angles (˚)
Tap 0 psig	152.1 ± 5.5	130.1 ± 4.2	22.0 ± 3.6
Tap 1 psig	158.0 ± 3.5	138.4 ± 1.3	19.5 ± 3.5
Continuous 0 psig	157.3 ± 4.5	126.8 ± 7.3	30.5 ± 6.4
Continuous 1 psig	163.8 ± 3.6	134.9 ± 6.8	28.8 ± 6.9

Some key observations from this data are that the internal angle of the human body is always larger than the CHAPS angle (total average of all tests was 25.2 ± 6.8˚) as seen in Fig. 6; larger internal and external angles were observed in the pressurization data versus unpressurized; and the continuous method had larger angles for the internal angle and smaller for the external.

VI. LIMITATIONS OF IMUS

IMU systems have limitations and the optimal system must be selected for the right job. Typical limitations are in g-range, sensitivity, lag, filtering, and accuracy. A few issues were identified with the selected APDM system for this application and are described in this section.

The investigators found that the magnetometers were susceptible to magnetic interference, even from metal tabletops, which changes the orientation of the NWU coordinate frame. For the CHAPS testing there was little magnetic interference, but this should be monitored in all testing environments and can be displayed with custom Matlab code to show the data in real time. A study by Bachmann et al. in 2004 developed a guideline that errors can be avoided by maintaining an approximate distance of two feet from any source of disturbance[29].

For the elbow joint, the positioning of the IMUs was closely matched internally and externally, but as seen in Fig. 1, the IMUs are not exactly on the rotation axes of the arm. For this reason, it was desired to find the final three Euler angles before reducing any data. The final rotation axis data may therefore have some twist associated with the values and this data should be used as a proof of concept.

The CHAPS was not sized specifically for the subject in this test, and the suit is designed to be used nominally in the seated position. Had the experiments been performed with a perfectly fitting suit in the seated position, it is possible that the internal and external measurements would be more similar.

Dead reckoning is a technological issue for IMUs as they do not know their exact positions at any given time. This is why the "tap" methodology was tested, to try and have a reset point in physical space. The advancement of this technique is further explored in the next section. A common indicator of the difficultly of position tracking is from the occurrence of drift.

Pseudo markers can be estimated from video analysis. However, in future testing it would be ideal to have arm markers for validation in photos or videos.

VII. RECOMMENDATIONS FOR FUTURE SPACESUIT TESTING

The following are recommendations for future improved data acquisition testing with IMU systems for applications like spacesuit mobility.

IMU data could be verified by constructing a simple non-ferrous rig to test one degree of freedom at a time with known angles and potentially known rotation rates (motor activated).

Real time acquisition of Euler angles can be generated with Matlab code. The signal will be slightly lagged, but the instant validation of motion would be useful and more insightful. This could also be used for real time monitoring of a variety of spacesuit joints.

Position estimation would be a valuable addition to the capabilities of the IMU. The performance of the ADPM IMUs is marginal for position estimation, due to drift, without regular position fixes. ADPM has unreleased code that uses frequent position fixes (every 5 seconds) and velocity nulling to track IMU position; performance figures have not been released but a comparison of the estimate to video of an IMU is compelling. We attempted some trials using arm motion in which position fixes were provided using a tap between two IMUs. These events can be identified and used as position fixes. Analysis of these trials is on-going. If adequate performance can be demonstrated, either through position fixes and careful software correction, or via future hardware improvements, IMU position estimation would enable a variety of applications such as:

- Generating a point cloud that maps out space suit workspace envelopes using natural motions.
- Tracking displacement in all directions for standardized tasks such as using a tool, useful for tool and task optimization.
- Enabling more general motion capture without the cost and constraints of a vision-based system.

It is also recommended that future work in spacesuit motion tracking incorporate El-Gohary et al.'s (2011) linkage method.

VIII. CONCLUSIONS

This proof of concept research met the goal of demonstrating that measurements of the human body within a spacesuit can be taken in a novel method using inertial measurement units (IMUs). With IMUs it is possible to track internal versus external angles to figure out optimal spacesuit fit, energy expenditure, and work envelope. Refinement of the method should prove to be valuable while testing in analogue environments or out in the field without the need for a visual motion capture system. Future data could be collected during spaceflight and lead to improved spacesuit design.

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