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A HUMAN SYSTEMS INTEGRATION APPROACH TO INDUSTRIAL EXOSKELETON EVALUATIONS FOR THE USAF

Capt. Erich Maxheimer
Mr. Corey Shanahan
Ms. Andrea Wolf
Mr. Jeffrey Craig*
Dr. Daniel Mountjoy
Maj. Clifford Johnson
Capt. David Canzonetta

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Final Report

AIR FORCE RESEARCH LABORATORY
711TH HUMAN PERFORMANCE WING
HUMAN SYSTEMS INTEGRATION DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIAL COMMAND
UNITED STATES AIR FORCE

* Apogee Engineering

NOTICE AND SIGNATURE PAGE

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//signature//
CAPT. ERICH W. MAXHEIMER
Flight Commander, HSI Laboratory
Human Systems Implementation Division

//signature//
MAJ. CLIFFORD D. JOHNSON
Deputy, Human Systems Implementation Division
Human Systems Integration Directorate

//signature//
COL. PHILIP J. PREEN
Director, Human Systems Integration Directorate
711th Human Performance Wing

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Capt Erich Maxheimer, Mr. Corey Shanahan, Ms. Andrea Wolf, Mr. Jeffrey Craig*, Dr. Daniel Mountjoy, Maj Clifford Johnson, Capt David Canzonetta

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14. ABSTRACT

Exoskeleton technology is rapidly evolving within the military, medical, and industrial fields. USAF maintenance operations have identified potential applications for exoskeleton technology. However, they need support in identifying, comparing, and evaluating options. Additionally, there is concern that manufacturer performance claims are not always accurate and that certain systems may pose injury risks. To address these concerns, the Human Systems Integration Laboratory in the 711th Human Performance Wing performed exoskeleton market research and evaluations to enable operational units to make informed purchases. The laboratory supported units with small scale field evaluations and created a plan for in-house laboratory evaluations. The laboratory evaluation plan was not executed due to changes in funding and organizational structure. However, the plan is documented in this technical report and may be a useful resource for future exoskeleton evaluations.

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1.0 EXECUTIVE SUMMARY

Exoskeleton technology is rapidly evolving within the military, medical, and industrial fields. USAF maintenance operations have identified potential applications for exoskeleton technology. However, they need support in identifying, comparing, and evaluating options. Additionally, there is concern that manufacturer performance claims are not always accurate and that certain systems may pose injury risks. To address these concerns, the Human Systems Integration (HSI) Laboratory in the 711th Human Performance Wing performed exoskeleton market research and evaluations to enable operational units to make informed purchases. The laboratory supported units with small scale field evaluations and created a plan for in-house laboratory evaluations. The laboratory evaluation plan was not executed due to changes in funding and organizational structure. However, the plan is documented in this technical report and may be a useful resource for future exoskeleton evaluations.

2.0 INTRODUCTION

2.1 Overview of Exoskeletons

Exoskeletons are wearable devices that are intended to aid the operator in the performance of physical tasks. While the concept of exoskeletons has been around for decades, the actual use of these systems has been accelerating in recent years. There are three primary categories of exoskeleton technology: military, medical, and industrial. Military exoskeleton systems are geared towards increasing operator mobility and survivability. These systems can be designed to help soldiers carry heavy loads over rough terrain, incorporate heavy ballistics protection, or include built-in heads up displays. Medical exoskeleton systems are designed to assist the user with lost or damaged physiological function. Lastly, industrial exoskeleton systems are aimed at reducing fatigue and injury as well as increasing human performance in a manufacturing or production setting. These exoskeletons are intended to assist users who perform repetitive tasks, especially in difficult postures such as bending over, squatting, or reaching for overhead objects. Industrial exoskeletons can also be categorized as upper body, lower body, or back systems (Figure 1). Typically, each system has its own niche and rarely assists users with wide-ranging tasks.

Figure 1. Example Upper Body, Lower Body, & Back System

Exoskeleton systems can be further described based on how they are powered: passive (non-powered) or active (powered). Passive systems typically rely on potential energy generated by the user. This energy is stored in springs or elastic bands. Passive systems may also include static supports, such as tool holdings, to transfer loads to different parts of the body or to the ground. Active systems typically use a battery or external source of electricity to drive actuators or motors to apply forces. Compared to passive systems, active systems can free greater loads from the user. However, they tend to be heavier and more complex. The technology readiness level of active systems are still immature due to their complexity. Therefore, few active systems are commercially available, leading the HSI Laboratory to focus on passive systems.

The HSI Laboratory has concentrated on industrial exoskeleton systems due to a high rate of injury to aircraft maintainers. Passive industrial exoskeleton technology boasts significant potential to effect the Air Force community by mitigating injury risk and reducing levels of fatigue, especially for overhead tasks. Reducing fatigue in commonly used muscle groups can increase job efficiency because maintainers would require fewer on-the-job breaks due to pain or discomfort. Furthermore, the incorporation of exoskeletons could increase a user's quality of life, extend the longevity of the Air Force maintainer workforce, and boost unit morale. Despite numerous potential benefits, industrial exoskeletons present risks if employed in unsuitable settings. For example, the exoskeleton must adequately fit the user and properly transfer loads across muscle groups. Additionally, passive industrial exoskeletons are not intended to allow users to support heavier loads than would be permitted without the system. Rather, these systems are intended to allow users to perform the same job tasks and support the same loads with lower injury risks. Other potential risks include snag hazards, loss of balance, drowning, inability for emergency egress, pinching, surface abrasions, blunt force injury, and electrical hazard (shocks).

2.2 HSI Laboratory Exoskeleton History

Since exoskeleton technology is continually evolving, it is difficult to know which commercially available systems are best suited for particular tasks. Operational units in the Air Force have potential applications for exoskeletons, but need technical support to make informed implementation decisions for purchases. The HSI Laboratory first began exoskeleton work in 2016 when the Oklahoma City Air Logistics Complex at Tinker Air Force Base requested assistance evaluating the effectiveness of the FORTIS® exoskeleton system. Shortly after, the Warner-Robins Air Logistics Complex at Robins Air Force Base and the Ogden Air Logistics Complex at Hill Air Force Base requested assistance evaluating exoskeletons, including EksoBionics' EksoVest ™, SuitX's ShoulderX ™, and Levitate's AIRFRAME ™. At the time of the request, no other USAF organizations were knowledgeable on exoskeletons.

From 2016 to 2019, the HSI Laboratory acquired multiple market-leading exoskeleton systems and testing equipment. The Laboratory also conducted extensive market research on emerging systems, attended Department of Defense (DoD) technical interchanges, established standards development committees with the American Society for Testing and Materials (ASTM), provided consultation to USAF squadrons upon request, and participated in working groups across the DoD, academia, and industry. During these years, other Air Force units have expressed interest in evaluating exoskeletons. These include the 461st Maintenance Squadron at Robins Air Force Base and the 366th Medical Group at Mountain Home Air Force Base (AFB).

Specific support included assistance with task identification, evaluation test planning, and the design of surveys to capture user experience/evaluation data. Additionally, HSI Laboratory's exoskeletons were provided where needed. The 461st Maintenance Squadron evaluation is currently in progress, whereas the Mountain Home AFB evaluation is in initial planning stages.

HSI Laboratory team members have shared or learned about exoskeletons at numerous events, including those in Table 1. In addition to these activities, the Laboratory published a "Technology Flash" which was specifically marketed to the Air Force Sustainment Center (AFSC). This tailored piece of information was distributed throughout the AFSC maintenance community.

Table 1. HSI Laboratory Attended Exoskeletons Events

DATE	EVENT
MAR 2017	National Defense Industrial Association Human Systems Conference
JULY 2017	Rapid Global Mobility Science and Technology Governance Meeting
OCT 2017	Airlift Tanker Conference
OCT 2017	Industry/DoD Technical Interchange hosted by Boeing & Navy's Puget Sound Naval Shipyard
NOV 2017	Joint Exoskeleton Executive Steering Committee Meeting
2017	National Institute for Occupational Safety and Health Event
2018	Ohio Bureau for Workers' Compensation Event
APR 2018	DoD Exoskeleton Technical Interchange Meeting
OCT 2018	ErgoX Symposium
NOV 2018	United States Special Operations Command/Tactical Assault Light Operator Suit/Air Force Research Laboratory Wearable Technologies Interchange
MAR 2019	WearRAcon 19 Conference
APR 2019	DoD Human Factors Engineering Technical Advisory Group
AUG 2019	Military Health Systems Research Symposium
AUG 2019	Team Aerospace Operational Solutions Conference
OCT 2019	ErgoX Symposium

Separately, members of our HSI Laboratory were active participants in the Navy-led DoD Industrial Human Augmentation Technology Working Group. The Laboratory also established a partnership with the Naval Aeromedical Research Unit at Dayton (NAMRU-D) for biodynamics and biomechanics assessments. Additionally, the HSI Laboratory and the Ohio State University's Spine Research Institute reached the initial collaboration stages of an effort to identify potential spinal loading impacts and injury risks during the use of exoskeletons.

To develop exoskeleton standards, ASTM formed a committee to address different areas of interest. Specifically, the HSI Laboratory supported the creation and continuing work of F48.01 (Human Factors sub-committee), F48.02 (Ergonomics sub-committee), and F48.91 (Terminology sub-committee).

Finally, the HSI Laboratory provided consultations to various units, as described in Table 2:

Table 2. HSI Laboratory Consultation Efforts

Organization	HSI Laboratory Consultation Summary
Air Force Sustainment Center	Provided technical support in Small Business Innovative Research (SBIR) evaluations
Army Research Lab	Produced white paper evaluations
Air Force Research Laboratory Center for Rapid Innovation	Delivered test plan support on SBIR effort for Air Mobility Command Port Delivery System
Air Mobility Command	Authored a Rapid Innovation Fund initiative and provided associated technical expertise in support of Aerial Port of the Future Concept, a program sponsored by Air Force Life Cycle Management Center, Agile Combat Support.

2.3 HSI Laboratory Exoskeleton Vision

Ultimately, the vision of the HSI Laboratory was to be the Air Force subject matter experts on industrial exoskeleton technology to support units in identifying exoskeleton systems to optimize their current job task performance while providing the lowest injury risk to their airmen. The top priorities for the HSI Laboratory as it pertains to exoskeletons are to improve safety and prevent injuries. It is crucial to the HSI Laboratory that exoskeleton technology is evaluated through a methodical approach. While the Laboratory recognizes the potential benefits of this technology, it is important to ensure these systems do not cause unknown harm over time, primarily to the neck and spine. For example, the Ohio State University's Spine Research Institute discovered that a system highly marketed to reduce fatigue and injury actually exposed users to unsafe forces on the spine (Marras, 2018). Furthermore, initial field evaluations prevented the Tinker Air Logistics Complex from pursuing acquisition of this system.

3.0 PROPOSED PROCEDURES

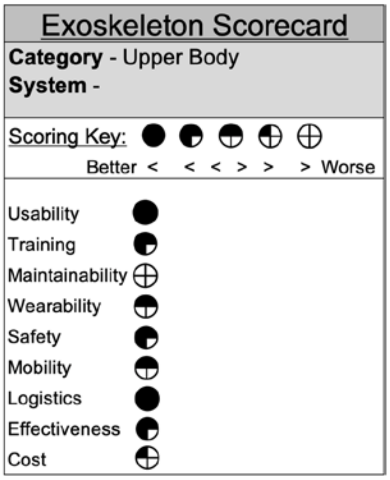
The HSI Laboratory created an evaluation plan to achieve its vision of acting as consultation subject matter experts to the Air Force. In general, the evaluation plan was created to provide USAF units with a quick and user friendly guide to understand the benefits and drawbacks of commercially available exoskeleton systems. While the evaluation plan was not executed due to funding issues, it is documented in this section to assist other units in future efforts.

3.1 Proposed Metrics

Standard metrics are necessary to objectively evaluate and compare exoskeleton systems. At the time of this report, literature review of exoskeletons results in few evaluation strategies. There is also a lack of standards in the broader community to objectively compare exoskeleton systems. The ASTM F48.02 Ergonomics Task Group has not yet released a detailed set of metrics for evaluating exoskeletons.

A standard set of metrics is needed to objectively compare exoskeleton systems. Since there is currently no established standard approach for system evaluations, the HSI Laboratory developed an evaluation rubric (Appendix A) based on the System Usability Scale (Jordan, 1996), user feedback, and Human Systems Integration best practices. This rubric is structured in ten broad categories; Usability, Training, Maintainability, Wearability, Safety, Mobility, Logistics, Effectiveness, Biomechanical/Physiological, and Cost. Each of these categories is made up of a number of sub-categories. These sub-categories are both quantitative and qualitative and are relevant to the respective categories that they populate. When evaluating a given system, the scores for each sub-category in a given category could be merged to create an overall category score.

An Exoskeleton Scorecard, Figure 2, would provide units with a simple description of the benefits and drawbacks of a given exoskeleton. However, Multi-Objective Decision Analysis considerations should be considered when creating a value system which combines different metrics. For example, if a method simply averages the scores for each metric in a category, it is being assumed that each metric in that category is of equal importance, which may not necessarily be true. Therefore the importance, or weight, of a metric must be decided appropriately for each sub-category.



Exoskeleton Scorecard

Category - Upper Body
System -

Scoring Key: ● ◕ ◑ ◔ ○
Better < < < > > > Worse

Usability	●
Training	◕
Maintainability	○
Wearability	◑
Safety	◕
Mobility	◑
Logistics	●
Effectiveness	◕
Cost	◔

Figure 2. Notional Exoskeleton Scorecard

3.2 Proposed Equipment

The HSI Laboratory intended to collect the necessary data to score all categories except for the Mobility category, Spinal Loading sub-category, and Motion Efficiency sub-category. These exceptions would be collected by university and DoD partners with specialized equipment. The major equipment items needed for the HSI Laboratory to evaluate the in-house effort included the Position and Load Test Apparatus for Exoskeletons (PoLoTAE), a heart rate monitor, an anthropometry kit, and the exoskeletons to be evaluated.

All testing and evaluations are intended to be standardized and repeatable. Therefore a set of uniform tasks had to be established by which a large portion of evaluation data would be gathered. In pursuit of this goal, the National Institute of Standards and Technology (NIST) developed the PoLoTAE, shown in Figure 3. The PoLoTAE allows subjects to perform industrial-style job tasks representative of overhead work, lifting, load alignments, and applied force. The HSI Laboratory formed the evaluation test plan around these standardized tasks. The standardized tasks are Applied Force, Load Alignment, Load Hanging, Load Positioning, and Peg-In-Hole. For more detailed information about the PoLoTAE and its function, refer to "Towards Standard Exoskeleton Test Methods for Load Handling" (Bostelman, 2019).

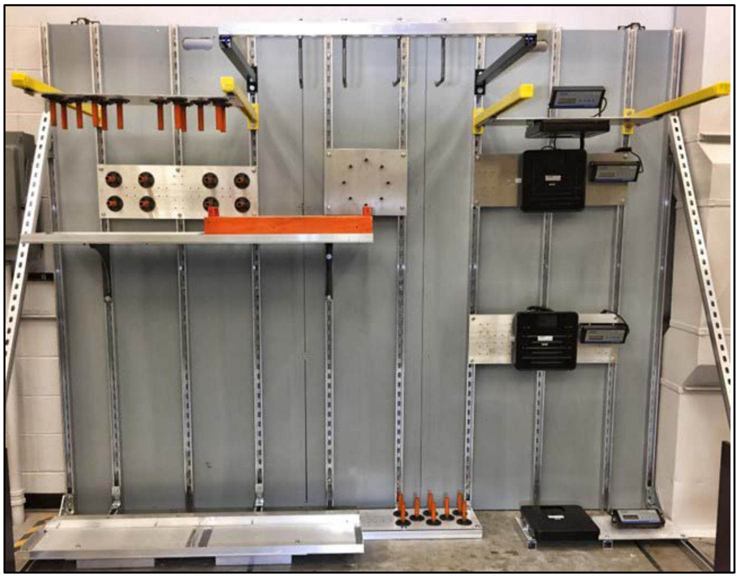


Figure 3. Position and Load Test Apparatus for Exoskeletons

Another important aspect of the HSI Laboratory's evaluations is monitoring the heart rate of subjects while tasks are being performed. Heart rate is of interest due to its known correlation to VO_2 during moderate levels of workload (Sanders, 1993). This correlations makes heart rate a preferred method for estimating workload since heart rate monitors are inexpensive and not inhibiting to task performance. While there are numerous models of heart rate monitors which could be used for these evaluations, the HSI Laboratory planned on utilizing the GoX Laboratory's system because it provides a real-time plot of heart rate vs. time.

The HSI Laboratory planned to use a GPM Anthropometry Kit to collect anthropometry measurements. These measurements could provide insights on how the fit of the exoskeleton effects user satisfaction or system performance. The Laboratory also intended to utilize a Vitus whole body scanner to collect 3D measurements of the subjects.

HSI Laboratory evaluations of exoskeletons were to be split into three sets based on the function of each system; i.e. upper body, lower body, and back. Due to the high frequency of overhead job tasks in the Air Force maintenance community, the first round of evaluations would focus on upper body exoskeletons. Three systems were slated to be evaluated in this initial round: EksoBionics' EksoVest ™, Levitate's AIRFRAME ™, and SuitX's ShoulderX ™. These systems were selected because they have garnered the most interest by Air Force maintenance units.

3.3 Proposed Methods

There are multiple means to collect the data in the Evaluation Rubric. Some of the metrics are simply based on expert review or manufacturer reported information. However, the metrics based on participant trials of tasks performed on the PoLoTAE require additional considerations.

The experiment proposed 5 participants with 20 PoLoTAE trials per participant. Each trial is a combination of a PoLoTAE task (Applied Force, Load Align, Load Hanging, Load Positioning, and Peg-In-Hole) and exoskeleton condition (wearing the EksoVest ™, ShoulderX ™, AIRFRAME ™, and no exoskeleton). Every combination of the 5 tasks and 4 conditions results in the 20 trials for each participant. Five participants are proposed to allow for a counterbalanced experiment to remove any confounding variable. Each participant would perform the trials in a different order than the others.

Before the first session, the participant would fill out the demographic section of the User Questionnaire (Appendix B) and a Laboratory member would collect anthropometry measurements. After each session, the participant would be asked to fill out the questionnaire, except for the last page which would be completed 24-48 hours later.

Specific details related to the PoLoTAE tasks need to be considered. For example, task duration was not determined; however, the duration for each specific task must be the same in all four conditions. The duration or number of repetitions that stresses participants must be defined, within reason. Also, neither the number of tasks to be performed on each day of testing nor the rest duration between each task were defined. However, these items should be standardized for all subjects and closely followed.

Finally, the HSI Laboratory was relying on the Ohio State University (OSU) Spinal Research Institute (SRI) for the Spinal Loading metrics. The researchers planned to use Electromyography (EMG) Biomechanical Models to evaluate local stress and spine tissue loads, Figure 4. This information could inform injury risks.

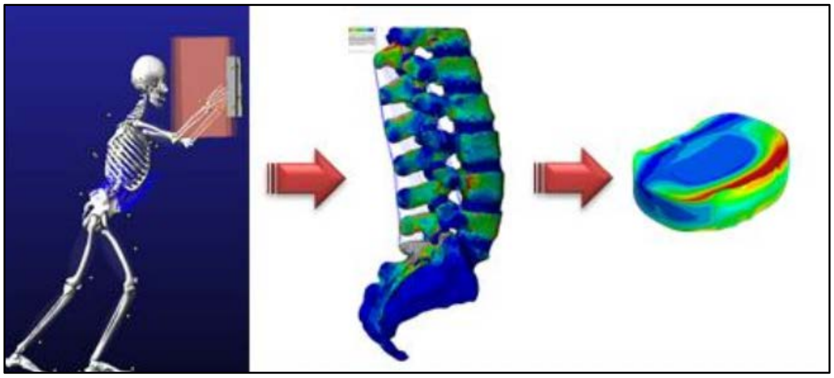


Figure 4. EMG-driven Biomechanical Model

Additionally, the HSI Laboratory was partnering with NAMRU-D to score the Mobility Category and Motion Efficiency sub-category metrics. They planned to use combinations of EMG and Inertial Measurement Unit (IMU) sensors to evaluate muscle utilization and spine tension. Real-time motion capture and balance measuring equipment could be used to compare the systems and search for difference in efficiency or risks (Figure 5).

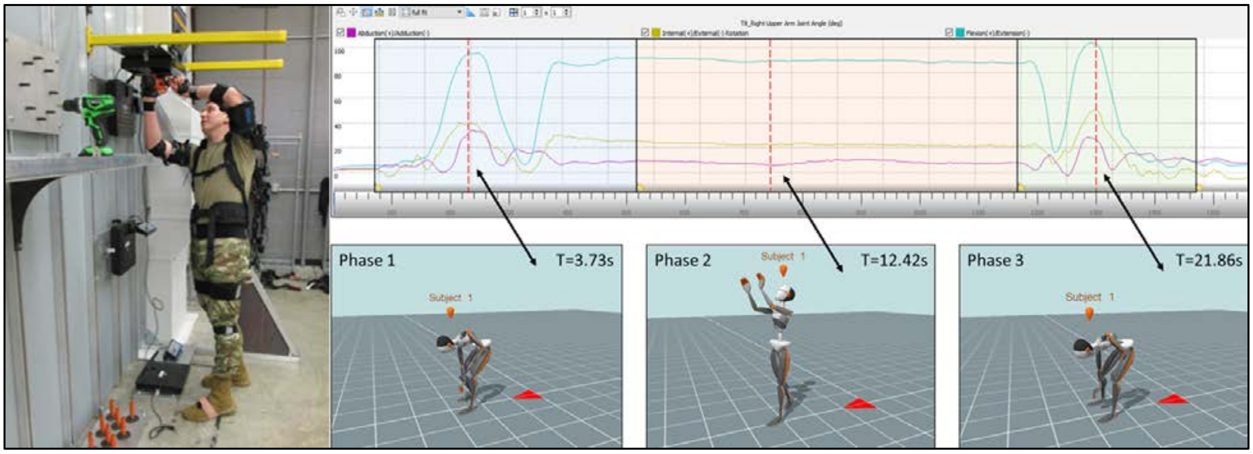


Figure 5. Motion Capture Analysis

4.0 FINAL RECOMMENDATIONS

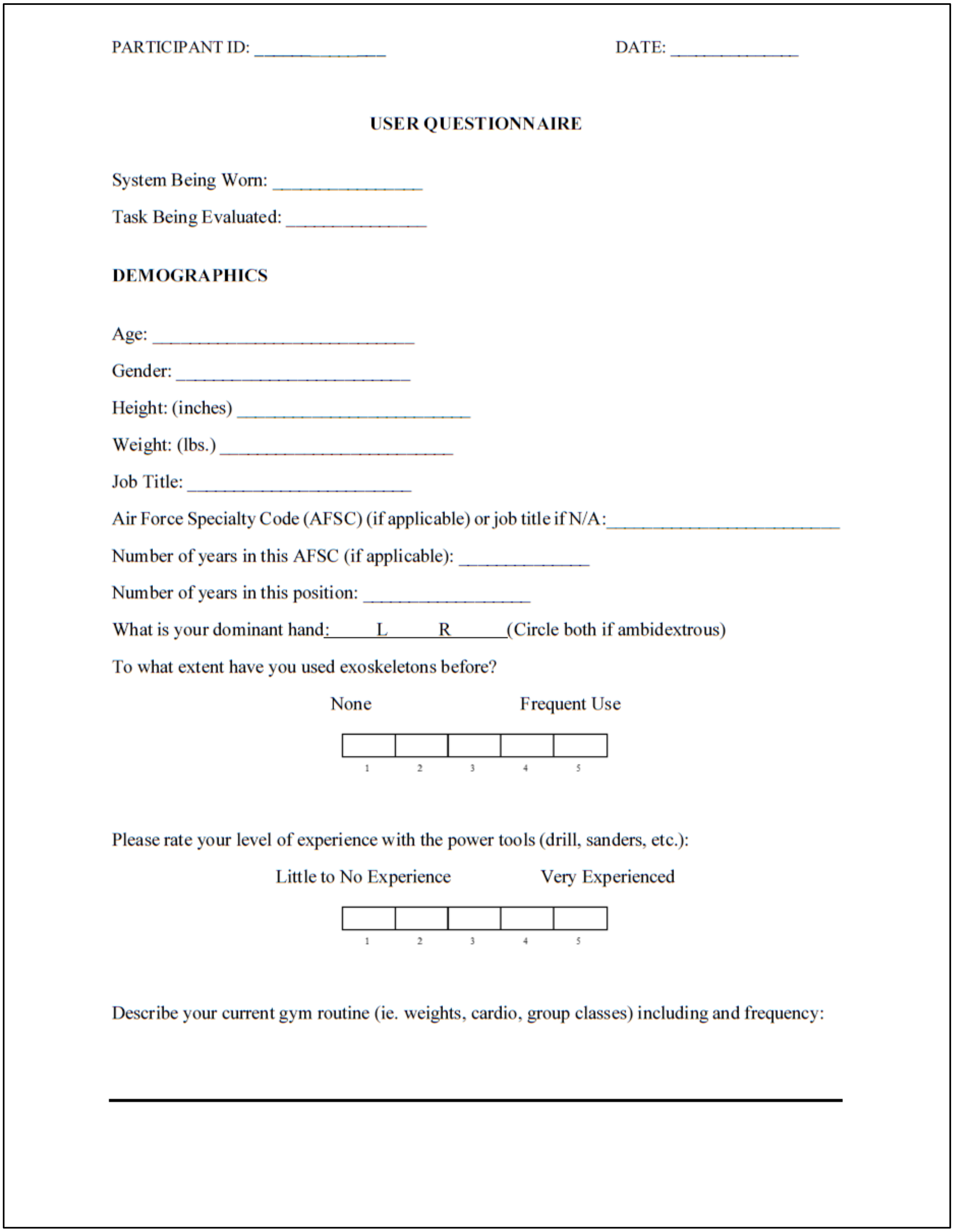
Exoskeleton work conducted in the HSI Laboratory sheds light on important takeaways. Firstly, manufacturer claims may be misleading so it is important to verify the usefulness of an exoskeleton before committing to its use. In general, exoskeletons are like any other tool – use the right one for the job. Typically, an exoskeleton is only useful for a narrow range of repetitive tasks. When one is used for the wrong job, it is likely to reduce productivity and increase injury risk. It is also clear that research gaps still exist with understanding the long term effects of exoskeleton use. Large scale longitudinal studies are necessary to fully understand the implications of these long term effects. Finally, formal system requirements should be defined by DoD units which are seeking to bridge a performance gap. Documented requirements would lay the groundwork for appropriate exoskeleton research. Given enough demand, a central organization could be created to manage the lifecycle of these systems.

5.0 BACK MATTER

5.1 Appendix A, Evaluation Rubric

Category	Sub-Category	Data Collection Method	Metric
Usability	Intuitiveness - User	User Questionnaire	Likert Scale
	Intuitiveness - Expert	Expert Review	Likert Scale
	Initial Fitting Time	Timed Trials	Seconds
	Don Time - After Training	Timed Trials	Seconds
	Doff Time - After Training	Timed Trials	Seconds
	Subjective Satisfaction	User Questionnaire	Likert Scale
Training	Training Required by Distributor?	Expert Review	Binary & cost
	Initial Training Duration	Expert Review	Seconds
	Recurring Training Required?		Binary & cost
	Quality of User Manual / O&M Docs	Expert Review	Likert Scale
	Customer Support	Expert Review	Likert Scale & Cost
	Training Effectiveness	User Questionnaire	Likert Scale
Maintainability	Ease to wash contact parts	Expert Review	Likert Scale & Cost
	Ease to clean exterior	Expert Review	Likert Scale & Cost
	Repairablity - Inhouse vs Contractor	Expert Review	Binary & Cost
	Ruggedness and Build Quality	Expert Review	Likert Scale
	Customer Support	Expert Review	Likert Scale & Cost
	Spare Parts Availability	Expert Review	
	Warranty Options	Manufacturer Reported	Binary & Months
	Useful Service Life	Manufacturer Reported	Minutes
	Battery Life	Manufacturer Reported	Minutes
Wearability	Topical Pain / Interface Pain	User Questionnaire	Likert Scale
	Musculoskeletal Pain - During Task	User Questionnaire	Likert Scale
	Musculoskeletal Pain - Next Day	User Questionnaire	Likert Scale
Safety	Emergency Doff Time	Timed Trials	Seconds
	Snag Hazard	Expert Review	Likert Scale
	Balance	Sway Measuring Equipment	
	Personal Protective Equip Compatability	Expert Review	
Mobility	Walking	User Questionnaire and Motion Capture	
	Stairs	User Questionnaire and Motion Capture	
	Mounting / Dismounting Vehicles	User Questionnaire and Motion Capture	
	Ladder / Scaffolding	User Questionnaire and Motion Capture	
	Range of motion	User Questionnaire / Motion Capture / Goniometer	
	Crawling	User Questionnaire and Motion Capture	
	Confined Space Compatability	Motion Capture or Body Scanner	
Logistics	Size Options	Manufacturer Reported	Number of Sizes
	Storage Requirements	Physical Size Measurement of Complete System	Cubic Feet
	Electricity Requirements	Manufacturer Reported	Binary or Voltage / Amps
	Laundry Machine / Service	Binary	Binary
	Configuration Control / Markings	Expert Review	Description / Likert Scale
	Packaging	Expert Review	Likert Scale
Effectiveness	Productivity	PoLoTAE Tasks	Task Performance
	Injury Risk Reduction	RULA / REBA	RULA or REBA Score
	Load Reduction	Force Measuring Equip	Torque or Force
	Fatigue Reduction	PoLoTAE Tasks	
Biomechanical Physiological	Spinal Loading	Spine Loading Analysis H/W and S/W	
	Workload / Energy Consumption	Heart Rate Monitor	Heart Rate
	Perceived Workload	User Questionnaire	Borg Scale
	Motion Efficiency	Optical & Inertial Limb Motion Tracking Equip	
Cost	Ease of purchase	Expert Review	US vs Foreign Distributor / GSA Sold
	Initial Cost	Expert Review	Monetary Cost
	Repair Cost	Expert Review	Monetary Cost
	Warranty Cost	Expert Review	Monetary Cost
	Training Cost	Expert Review	Monetary Cost

5.2 Appendix B, User Questionnaire



PARTICIPANT ID: _______________ DATE: ______________

USER QUESTIONNAIRE

System Being Worn: ________________

Task Being Evaluated: _______________

DEMOGRAPHICS

Age: ____________________________

Gender: _________________________

Height: (inches) _________________________

Weight: (lbs.) _________________________

Job Title: ________________________

Air Force Specialty Code (AFSC) (if applicable) or job title if N/A:_________________________

Number of years in this AFSC (if applicable): ______________

Number of years in this position: __________________

What is your dominant hand:_____L_____R______(Circle both if ambidextrous)

To what extent have you used exoskeletons before?

None Frequent Use

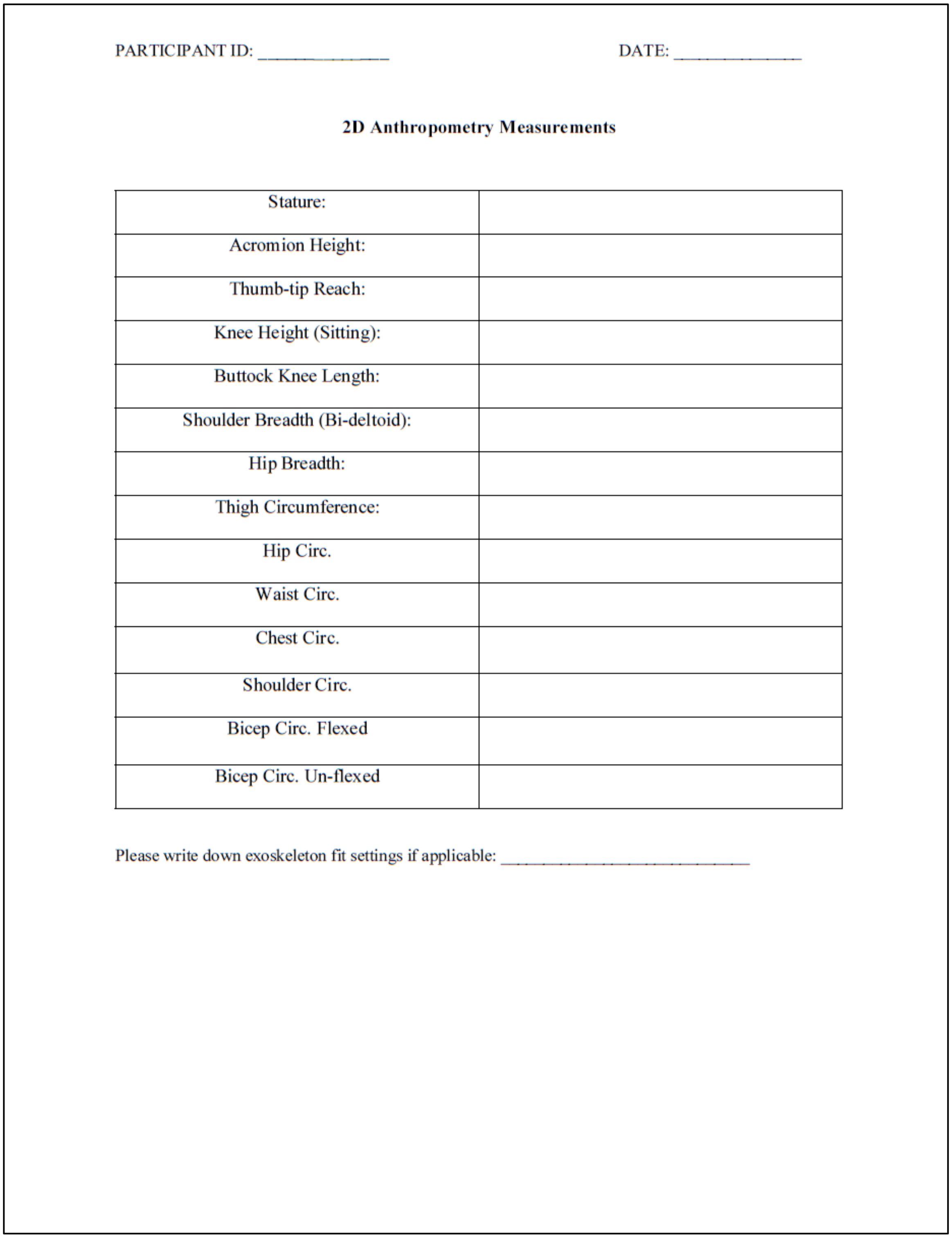
☐	☐	☐	☐	☐
1	2	3	4	5

Please rate your level of experience with the power tools (drill, sanders, etc.):

Little to No Experience Very Experienced

☐	☐	☐	☐	☐
1	2	3	4	5

Describe your current gym routine (ie. weights, cardio, group classes) including and frequency:

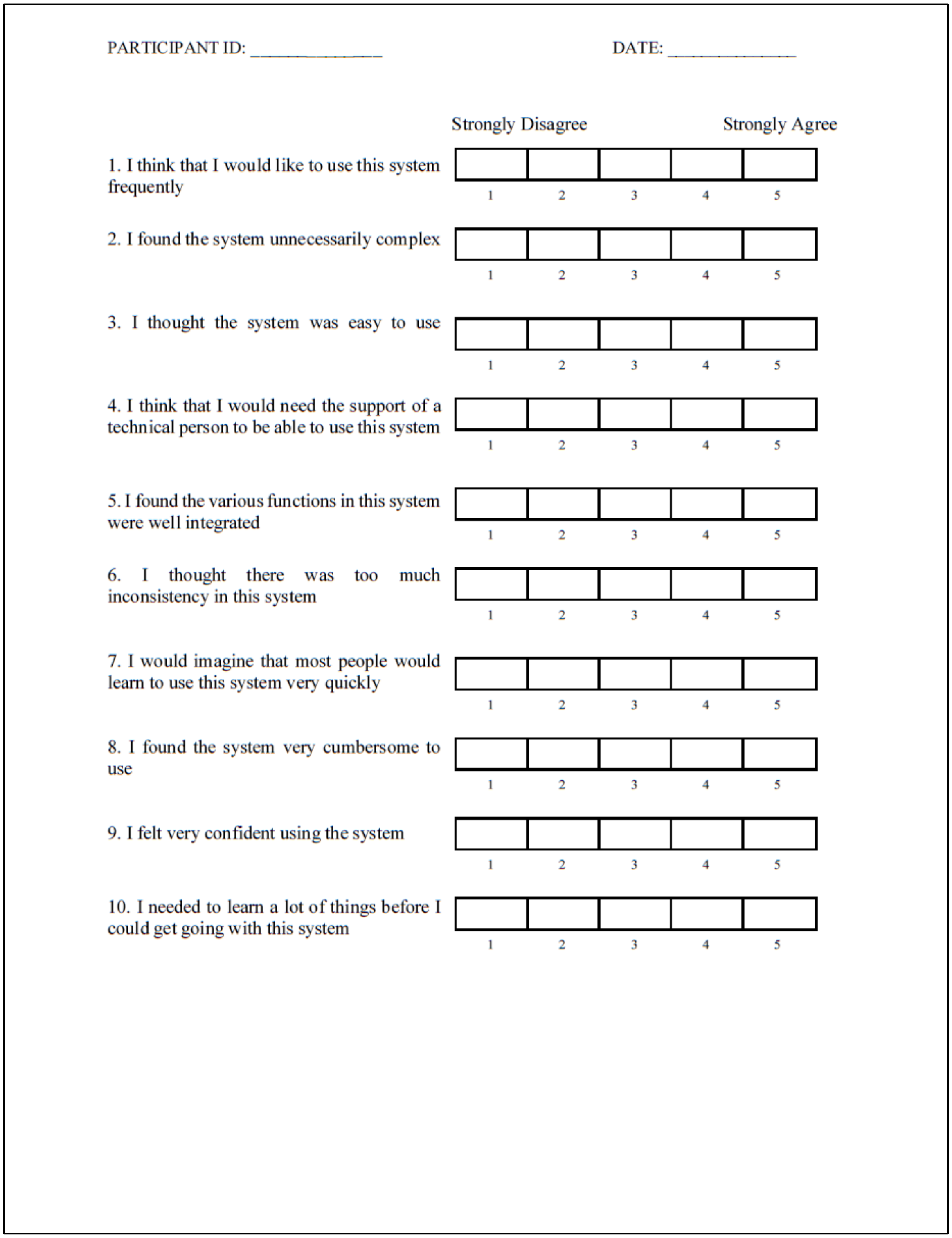


PARTICIPANT ID: ______________ DATE: ______________

2D Anthropometry Measurements

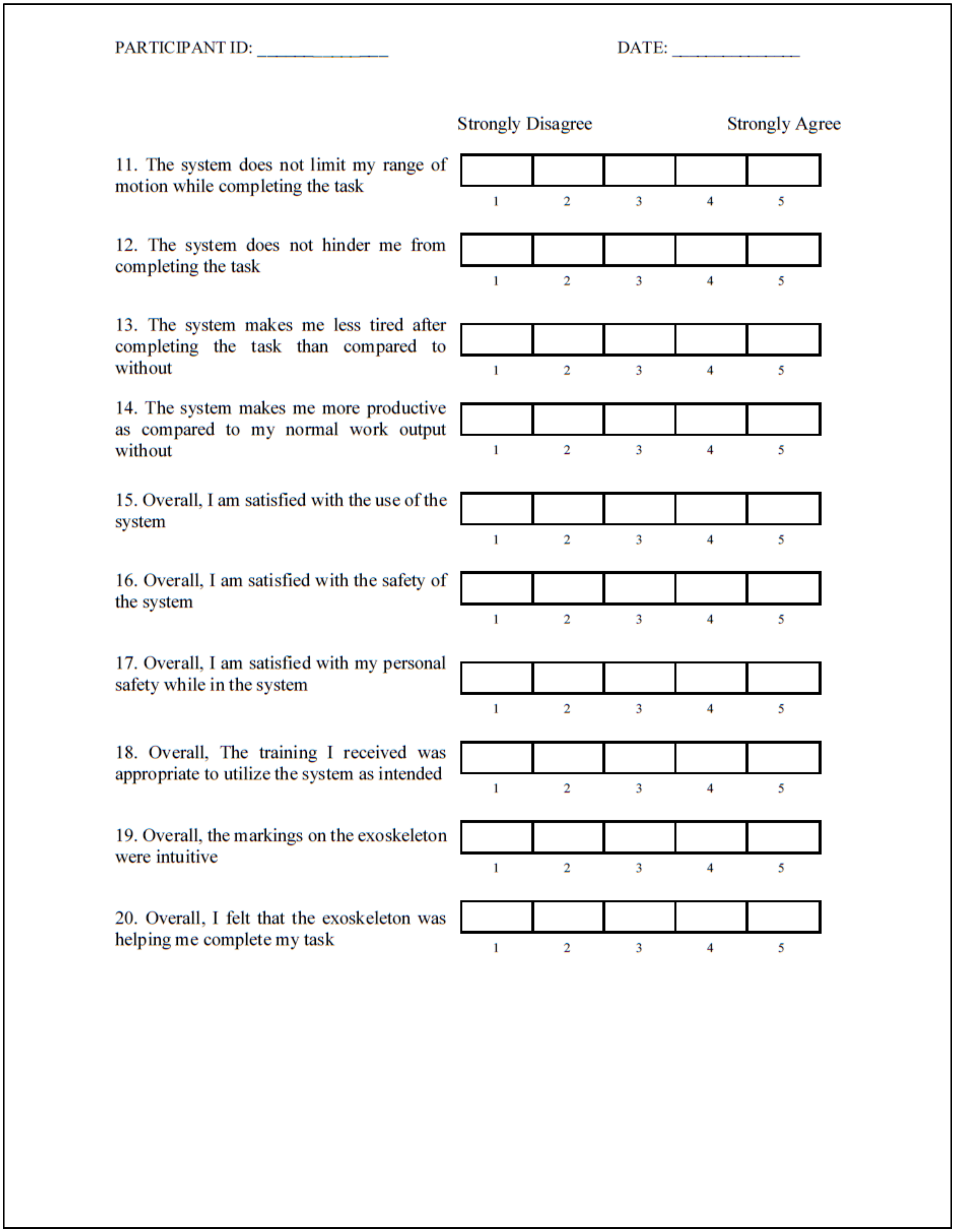
Stature:	
Acromion Height:	
Thumb-tip Reach:	
Knee Height (Sitting):	
Buttock Knee Length:	
Shoulder Breadth (Bi-deltoid):	
Hip Breadth:	
Thigh Circumference:	
Hip Circ.	
Waist Circ.	
Chest Circ.	
Shoulder Circ.	
Bicep Circ. Flexed	
Bicep Circ. Un-flexed	

Please write down exoskeleton fit settings if applicable: ___________________________



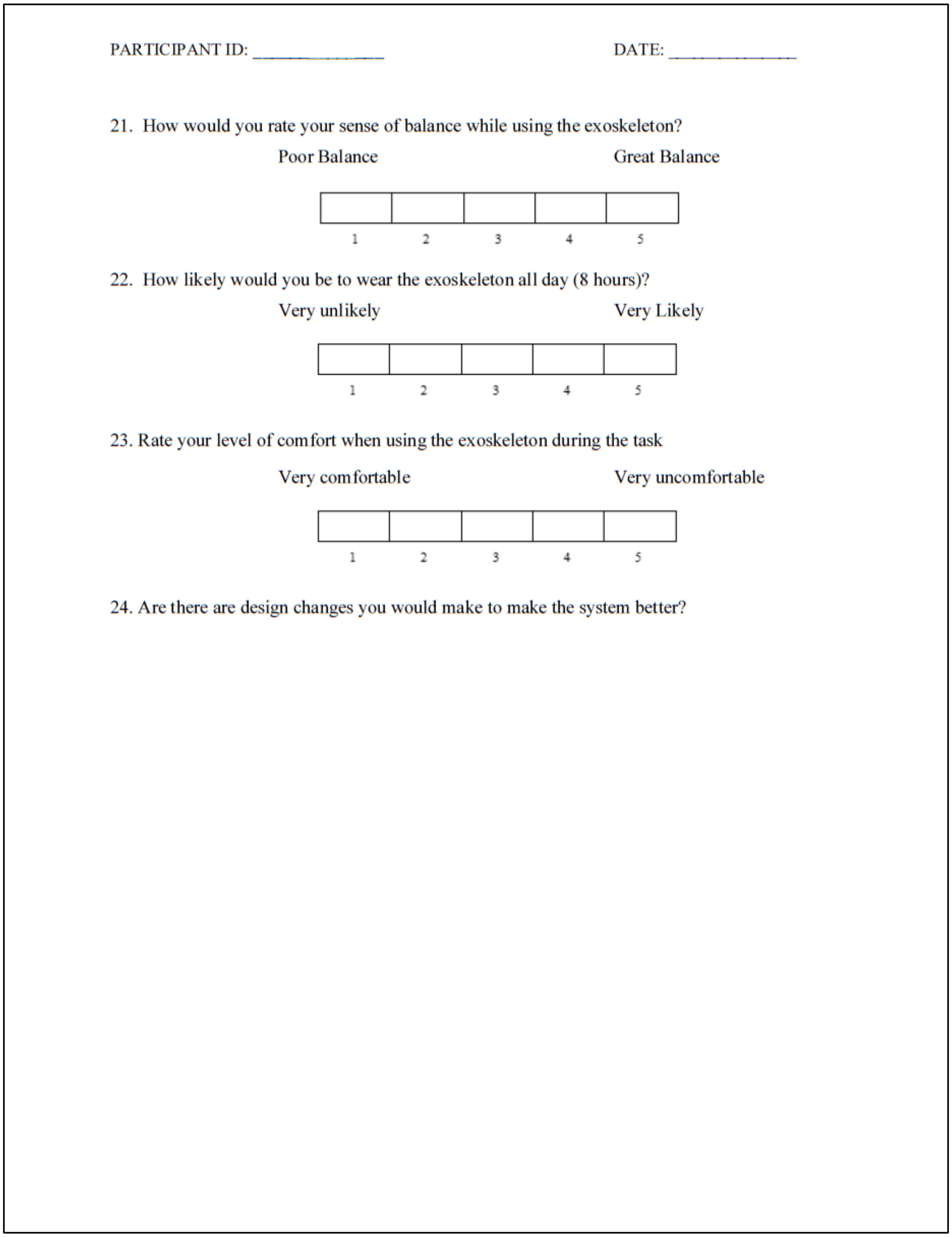
PARTICIPANT ID: ______________ DATE: ______________

	Strongly Disagree				Strongly Agree
1. I think that I would like to use this system frequently	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2. I found the system unnecessarily complex	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
3. I thought the system was easy to use	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
4. I think that I would need the support of a technical person to be able to use this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
5. I found the various functions in this system were well integrated	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
6. I thought there was too much inconsistency in this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
7. I would imagine that most people would learn to use this system very quickly	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
8. I found the system very cumbersome to use	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
9. I felt very confident using the system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
10. I needed to learn a lot of things before I could get going with this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5



PARTICIPANT ID: ______________ DATE: ______________

	Strongly Disagree				Strongly Agree
	1	2	3	4	5
11. The system does not limit my range of motion while completing the task	☐	☐	☐	☐	☐
12. The system does not hinder me from completing the task	☐	☐	☐	☐	☐
13. The system makes me less tired after completing the task than compared to without	☐	☐	☐	☐	☐
14. The system makes me more productive as compared to my normal work output without	☐	☐	☐	☐	☐
15. Overall, I am satisfied with the use of the system	☐	☐	☐	☐	☐
16. Overall, I am satisfied with the safety of the system	☐	☐	☐	☐	☐
17. Overall, I am satisfied with my personal safety while in the system	☐	☐	☐	☐	☐
18. Overall, The training I received was appropriate to utilize the system as intended	☐	☐	☐	☐	☐
19. Overall, the markings on the exoskeleton were intuitive	☐	☐	☐	☐	☐
20. Overall, I felt that the exoskeleton was helping me complete my task	☐	☐	☐	☐	☐



PARTICIPANT ID: _______________ DATE: _______________

21. How would you rate your sense of balance while using the exoskeleton?

Poor Balance Great Balance

☐	☐	☐	☐	☐
1	2	3	4	5

22. How likely would you be to wear the exoskeleton all day (8 hours)?

Very unlikely Very Likely

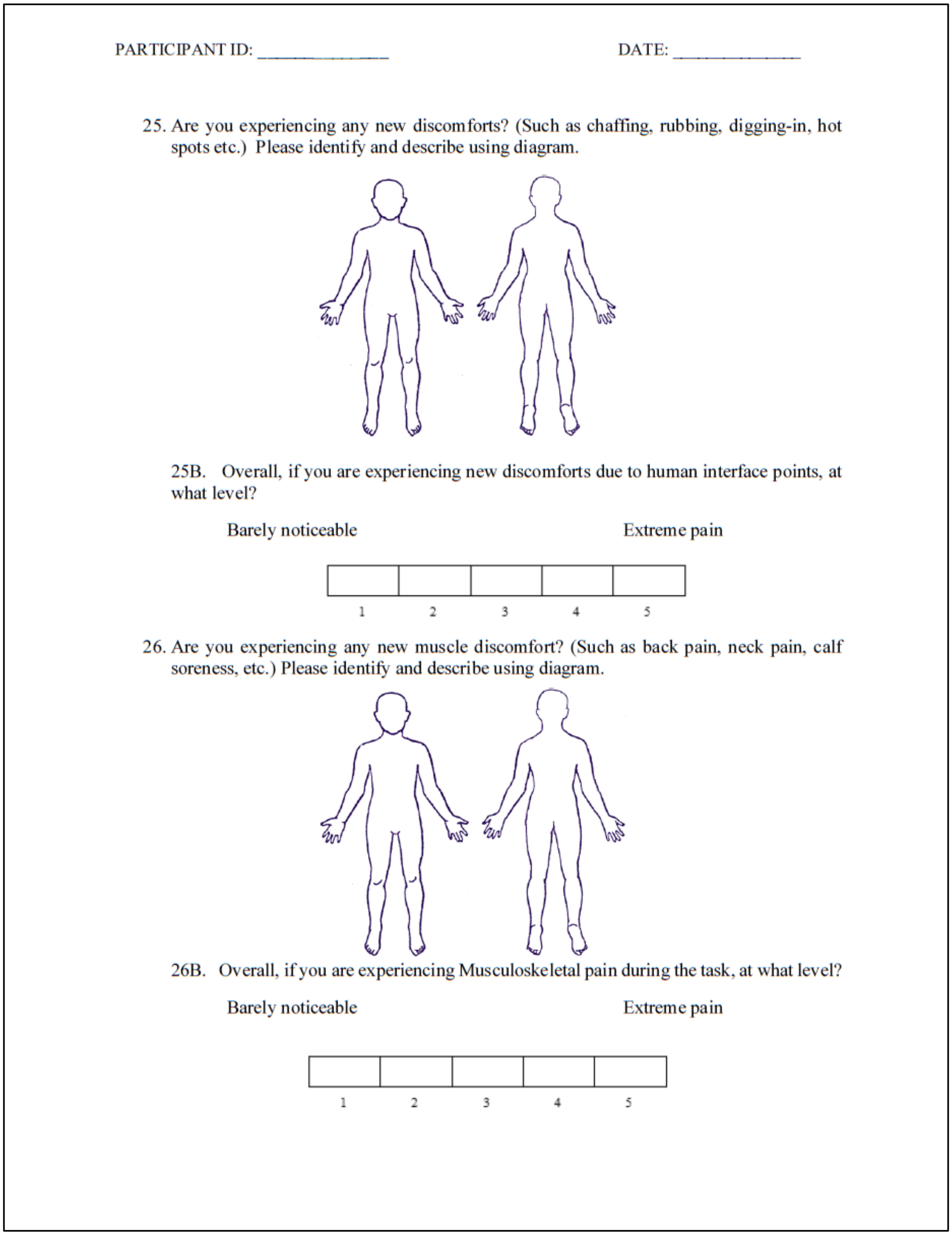
☐	☐	☐	☐	☐
1	2	3	4	5

23. Rate your level of comfort when using the exoskeleton during the task

Very comfortable Very uncomfortable

☐	☐	☐	☐	☐
1	2	3	4	5

24. Are there are design changes you would make to make the system better?



PARTICIPANT ID: _______________ DATE: _______________

25. Are you experiencing any new discomforts? (Such as chaffing, rubbing, digging-in, hot spots etc.) Please identify and describe using diagram.

25B. Overall, if you are experiencing new discomforts due to human interface points, at what level?

Barely noticeable Extreme pain

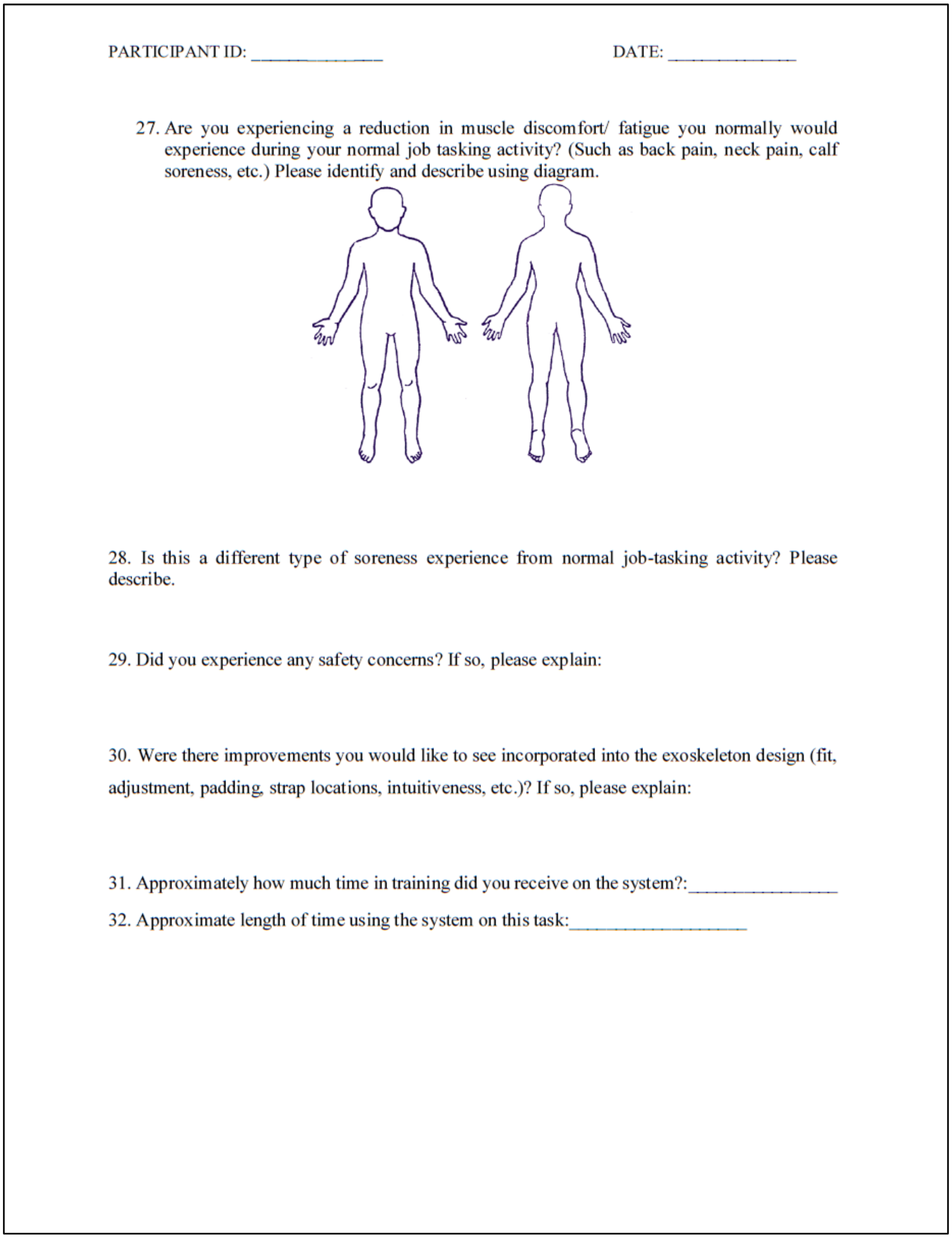
1	2	3	4	5

26. Are you experiencing any new muscle discomfort? (Such as back pain, neck pain, calf soreness, etc.) Please identify and describe using diagram.

26B. Overall, if you are experiencing Musculoskeletal pain during the task, at what level?

Barely noticeable Extreme pain

1	2	3	4	5



PARTICIPANT ID: _______________ DATE: _______________

27. Are you experiencing a reduction in muscle discomfort/ fatigue you normally would experience during your normal job tasking activity? (Such as back pain, neck pain, calf soreness, etc.) Please identify and describe using diagram.

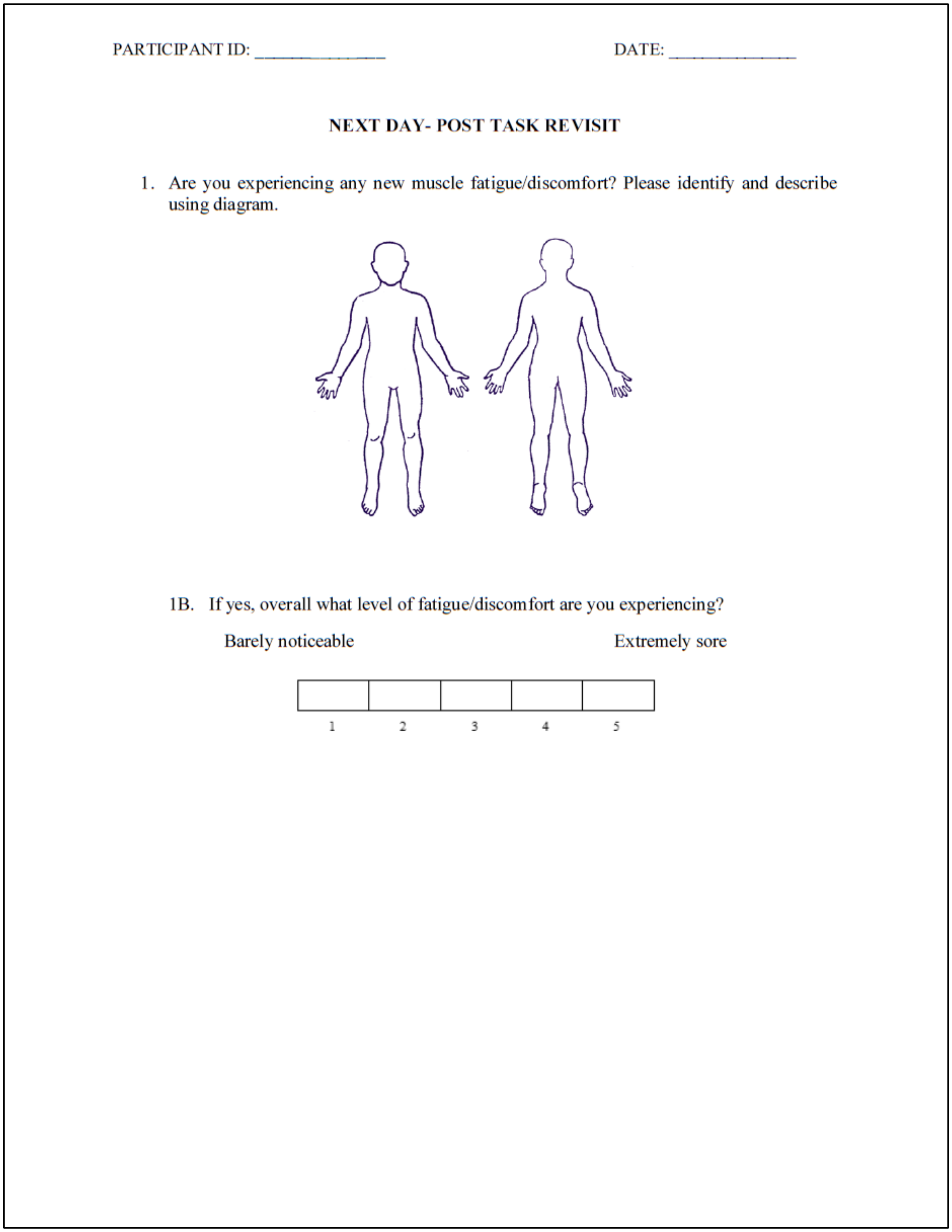
28. Is this a different type of soreness experience from normal job-tasking activity? Please describe.

29. Did you experience any safety concerns? If so, please explain:

30. Were there improvements you would like to see incorporated into the exoskeleton design (fit, adjustment, padding, strap locations, intuitiveness, etc.)? If so, please explain:

31. Approximately how much time in training did you receive on the system?:_________________

32. Approximate length of time using the system on this task:____________________



PARTICIPANT ID: _______________ DATE: _______________

NEXT DAY- POST TASK REVISIT

1. Are you experiencing any new muscle fatigue/discomfort? Please identify and describe using diagram.

1B. If yes, overall what level of fatigue/discomfort are you experiencing?

Barely noticeable Extremely sore

1	2	3	4	5

6.0 REFERENCES

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2. Jordan, P.W., Thomas, B., Weerdmeester, B.A., McClelland, I.L., Usability Evaluation in Industry, Taylor & Francis. Bristol, PA, 1996. pp. 189-194
3. Bostelman, R., Li-Baboud, Y. S., Virts, A., Yoon, S., & Shah, M. "Towards Standard Exoskeleton Test Methods for Load Handling," *2019 Wearable Robotics Association Conference (WearRAcon)*, IEEE, 2019, pp. 21-27
4. Sanders, M. S. and McCormick, E. J., Human Factors in Engineering and Design, McGraw-Hill, New York, NY, 1993, pp. 234-235

ACRONYMS

711 HPW	711 Human Performance Wing
711 HPW/HP	Human Systems Integration Directorate
ASTM	American Society for Testing and Materials
AFB	Air Force Base
AFSC	Air Force Sustainment Center
AFRL	Air Force Research Laboratory
DoD	Department of Defense
EMG	Electromyography
HSI	Human Systems Integration
IMU	Inertial Measurement Unit
NAMRU-D	Naval Aeromedical Research Unit at Dayton
NIST	National Institute of Standards and Technology
OSU	Ohio State University
PoLoTAE	Position and Load Test Apparatus for Exoskeletons
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
SBIR	Small Business Innovative Research
SRI	Spinal Research Institute
USAF	United States Air Force
VO_2	Oxygen Uptake