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Human Factors Assessment of the U.S. Naval Research Laboratory Limb Protection Program (QuadGard Phase III Pre-Pilot Production Design)

by Richard S. Bruno

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14. ABSTRACT
After visiting amputees in a military hospital in January 2004, the Secretary of the Navy, Gordon England, ordered the Office of Naval Research to develop body armor to envelop Soldiers'/Marines' limbs. This action resulted in a cooperative program cutting across services, industry, and academia to develop an armor system in less than 180 days. The U.S. Army Research Laboratory's Human Research and Engineering Directorate (HRED) provided human factors design guidance in the development of the QuadGard III limb protective system. HRED conducted limited human factors assessments to collect user feedback following static exercises and obstacle course negotiation. The static exercises showed little impact on body movements; however, the dynamics of the obstacle course required body movements that showed the configuration constricted movement. The participants reported configuration bulk and heat buildup. Compared to baseline condition (helmet and M4 rifle), obstacle course completion time was 16% greater when the baseline and outer tactical vest (OTV) were worn and 33% greater when wearing the baseline, OTV, and QuadGard arms and trousers. Recommended modifications of the QuadGard design configuration are to reduce and eliminate restrictions on the body in motion, improve air movement between the wearer and the armor, and improve the function of the configuration and user acceptance. Based on the results of this assessment, the U.S. Marine Corps System Command initiated phases IV and V QuadGard development.

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The efforts to develop the QuadGard Limb Protective Armor System are dedicated to the U.S. Armed Forces' men and women fighting in Afghanistan and Iraq.

The following members make up the cooperative/contributory QuadGard program team:

- Peter Matic, Ph.D., and Graham Hubler, Ph.D., U.S. Naval Research Laboratory, program managers
- Richard S. Bruno, Human Research and Engineering Directorate, U.S. Army Research Laboratory (ARL), human factors
- Nevin L. Rupert, Weapons and Materials Research Directorate, ARL, ballistics requirements
- W. C. Blethen, U.S. Army Aberdeen Test Center, ballistics testing
- J. Frost, FS Technology, Inc., contractor
- D. Branson, Oklahoma State University, material fabrication

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1. Introduction

After visiting amputees at the Bethesda National Naval Center, the Naval Medical Center Portsmouth, the Naval Health Research Center, and other military hospitals in January 2004, the Secretary of the Navy, Gordon England, ordered the Office of Naval Research (ONR) to develop body armor to envelop Marines'/Soldiers' limbs. This action resulted in a cooperative program cutting across services, industry, and academia to develop an armor system in less than 180 days. The performing team was the U.S. Naval Research Laboratory (program lead), the U.S. Army Research Laboratory (ARL), FS Technology, and Oklahoma State University with funding from ONR.

ARL's Human Engineering and Research Directorate (HRED) provided human factors design guidance in the development of the QuadGard limb protective system. The system represents a blend of ballistic protection, low weight, flexibility, mobility, and comfort. It provides mounted and dismounted Marines/Soldiers with an option for protection in operational situations where blast weapons and improvised explosive devices (IEDs) may be encountered, and it provides ballistic protection for arms and legs in response to blast weapon threats and combat casualty trends in Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF). This effort produced small numbers of prototypes in design phases I and II and culminated in the phase III design over the April 2004–2005 time period.

A novel design approach of "controlled casualty" (or "reduced casualty severity") was developed as a guiding principle behind the QuadGard system development. This design approach understands that any armor system can and will be overmatched. It stresses reducing the severity of the resulting injuries and amputation rates instead of only looking at reducing the overall casualty rate. As a result, this program has successfully demonstrated a 10-lb system with level IIA ballistic protection and an 11-lb system with level II ballistic protection that supplement the current Interceptor body armor. The designs are based on injury patterns, anatomical considerations, and human factor assessments to ensure compatibility, mobility, and troop acceptance for less than $1500 per set of QuadGard.

2. Information, Benefits, and Utility

The QuadGard phase III arm and leg armor (see figure 1) was designed from OIF combat casualty trends and blast threat analyses to protect against blast fragments and reduce the likelihood of severe injuries. The level of protection in the current design is National Institute of Justice (NIJ) level IIA, with options for levels II and IIIA. The objective of this effort was to develop a protective system that represents a blend of protection, low weight, flexibility,

Figure 1. QuadGard Phase III with interceptor outer tactical (OTV) vest.

mobility, and comfort to give mounted and dismounted Marines/Soldiers an option for protection in operational situations where blast weapons and IEDs may be encountered. However, stated performance is based on NIJ Standard 0101.04, *Ballistic Resistance of Personal Body Armor* (NIJ, 2001), an equipment standard developed by the Law Enforcement Standards Laboratory of the National Bureau of Standards. This standard is based on bullet performance, not fragmentation, and only suggests a relative measure of ballistic performance against fragmentation. No equivalent commercial fragmentation standard exists for describing the relevant protection levels.

In operational terms, the QuadGard ballistic protection can increase the nonlethal and safe operating area around an IED by reducing the minimum standoff distances from the Marine to the device. An associated reduction in injury severity can mean quicker return to duty (e.g., hours or days instead of weeks), reduced need for intensive medical treatment and rehabilitation (e.g., weeks instead of months), or the difference between injuries producing or not producing amputation disabilities.

Potential uses for the QuadGard armor include the following:

- Vehicle occupants/convoy crews
- Sentry and checkpoint duty
- Security and support operations

- Roadside patrols
- Explosive ordnance reconnaissance by explosive ordnance disposal (EOD) units
- Forward deployed medical personnel
- First elements of breaching parties

3. Threat Assessment and Guidance

Information about the blast weapon and IED threat was assessed from background information provided by ARL, U.S. Army Aberdeen Test Center, Navy EOD, National Ground Intelligence Center, and OIF and OEF briefs. There are many types of devices and methods of employment against Marines in OIF and OEF, and no “typical” IED exists.

The general consensus from these sources was that IEDs were based on explosives or blast weapons (e.g., artillery shells). These were generally devices of varying explosive yield deployed in no optimal fashion (e.g., buried in or on the ground and in no optimal orientations). The lethal radius of these devices is estimated to range from tens to hundreds of feet. There was no consensus about what constitutes a “typical” IED, since the designs evolve to reflect available materials and current operational tactics used by the insurgent forces (Rupert, 2004).

Although these devices often generate large fragments, small fragments often dominate the fragment yield of these devices. The velocities of these smaller fragments are below 2000 ft/s over significant areas around the blast, depending on the device and distance from the device, but are probably responsible for many lethal or severe injuries. These types of fragments can be stopped by soft armor at NIJ level IIA and higher levels of protection (NIJ, 2001).

This information guided the QuadGard design and is based on the following details. IEDs produced from conventional artillery munitions produced by NATO and the Warsaw Pact generate large numbers of 100- to 250-mg engineered fragments. Many of these fragments do not achieve maximum designed velocities because of the method of IED employment. Most IEDs are augmented with nails, washers, and bolts, which have inefficient aerodynamics and penetration of body armor. Gravel and sand fragments are entrained by IED blasts and are lower-velocity fragments. The low-velocity subsonic fragments produced by these blasts also pose a threat and can be stopped by soft armor at NIJ level IIA (ARDEC, 1985).

4. Medical Assessment and Guidance

Medical data and information were integrated from multiple sources, including the Walter Reed Army Medical Center, Bethesda National Naval Medical Center, the Naval Medical Center-Portsmouth, the Naval Health Research Center, ONR-Human Systems, and OEF and OIF briefs. The military medical personnel who had extensive experience in treating OIF and OEF casualties, from levels I–IV medical care and facilities, were consulted and provided general guidance to the design of prototypes over the course of the program (Pasquina, 2004).

An expected operational metric of this benefit should be shifting of injuries to International Red Cross injury classifications from higher to lower categories, e.g., open-compound, closed-compound, open-simple, and closed-simple categories for fractures. A shift to lower-injury categories brings lower probability of amputation or disability and a higher probability of return to duty (Coupland, 1992).

Quantitative methods to predict the effect of arm and leg body armor on blast injury severity from the IED threat are lacking. Current models such as Casualty Reduction and Integrated Casualty Estimation Methodology may be useful but generally focus on the effect of ballistic wounds on warfighter capabilities on the battlefield rather than on medical injury severity and long-term outcome.

The QuadGard arm and leg protection equipment was designed to address these specific medical concerns from the blast fragment threat posed by IEDs:

- Nerve and vascular bundle protection from fragments
- 360° knee and elbow joint protection.
- Lower abdomen protection for femoral arteries
- Lower back and buttocks protection for sciatic nerve
- Hip joint protection
- Shoulder joint overlap with the OTV

Although ballistic protection was the primary goal, additional secondary benefits of the arm and leg equipment are as follows:

- Protection against direct exposure to blast pressure waves
- Protection against flash burns not provided by combat blouse and trousers

5. Design Rationale

The QuadGard design incorporated the combat casualty and blast weapon threat information, balancing protection with the combination of weight, flexibility, and comfort. The design was based on integration with the Interceptor OTV with small arms protective insert (SAPI) plates. It was assumed that the groin protection option of the Interceptor would be used to protect the groin area. The design features and strategy are summarized in table 1.

Table 1. Design features and strategies.

Design Features	Design Strategy
Area of coverage	Cover medically vulnerable areas
Threat	Small fragments at moderate velocity
Level of protection	NIJ-level IIA (with II and IIIA options)
Thermal management	Segmented and vented design
Weight	10-lb maximum (<OTV with SAPI)
Comfort	OTV attachments and suspenders
Flexibility	Interactive elbow and fold away design at the knee joints
Mobility	Consistent with dismounted activities
Appearance	Consistent with warfighter image
Compatibility	Helmet, OTV, weapon, equipment
Use and maintenance	Comparable to OTV
Environmental durability	Comparable to OTV
Cost	$1500/set (comparable to OTV with SAPI)

6. Objectives

The objectives of the ARL HRED limited assessments were (1) to elicit user feedback regarding mobility from participants wearing the concept QuadGard III and (2) to provide human factors guidance to enhance/improve the QuadGard configuration.

7. Method and Procedure to Obtain User Feedback

Eight male enlisted military personnel participated in these assessments. There were four participants from the 16th Ordnance Battalion and four from the Marine Corps Detachment, both located at Aberdeen Proving Ground (APG), MD, at that time. Sizing system criteria for the

QuadGard armor were driven by having only a medium size available. Therefore, all participants were selected by stature: minimum 5 ft 5 in and a maximum of 5 ft 7 in. All participants were in excellent physical shape and had previously passed the U.S. Marine/Army Physical Fitness Test. User mobility of the QuadGard was assessed with the use of static exercises and the mobility portability obstacle course for dynamic exercises.

7.1 Static Exercises

A static exercise routine, which was used to assess a participant's performance, perceived range of motion, ease of movement, and overall compatibility of the QuadGard III, is listed in the appendix. Figure 2 shows a participant wearing the QuadGard III assuming the following body postures: kneeling, climbing and descending from a stairway and ladder, and throwing an inert grenade.

Figure 2. Participant wearing QuadGard III during static exercise assessment.

7.2 Mobility and Portability Obstacle Course

The ARL HRED mobility and portability obstacle course at APG consists of 20 individual obstacles spread over a serpentine course of about 500 m. The obstacles have been chosen to subject the participants to the kinds of maneuvers they should expect to perform in combat, such as running, jumping, climbing, balancing, crawling, and negotiating buildings, stairs, and windows (figure 3). If the weapon system being carried and items worn were incompatible, these problems would be noticeable during obstacle course runs. This obstacle course provides accelerated wear as a by-product of portability.

Figure 3. Participant wearing QuadGard III while negotiating the obstacle course.

Obstacle course equipment configurations and obstacle course presentation order were as follows:*

1. Baseline 3.0-lb helmet with 6.6-lb inert M4 rifle = 9.6 lb
2. Baseline (9.6 lb), OTV (8.4 lb), with QuadGard arms (3.0 lb) = 21.0 lb
3. Baseline, OTV with QuadGard arms and trouser (7.0 lb) = 28.0 lb

8. Participant/User Feedback Results

The participants identified a minor issue with the attached QuadGard III sleeve on the OTV. Insertion of a user's hand into the open QuadGard III sleeve was viewed as awkward or unconventional because it was not a common sleeve. The user's hand must be inserted toward the elbow area of the QuadGard III sleeve. This issue was overcome by equipment familiarization and practice. During the static exercise routine, one participant identified a problem with the trouser fit. The investigators noted that the participant had over-tightened the suspender, causing the trouser to hang improperly; this impacted the participant's ability to squat. No other problems were identified during the static exercises.

The mean user feedback ratings for the static exercises were calculated and are presented in figure 4. For the static exercises, the average ratings regarding leg movement and compatibility of the QuadGard III trouser were generally "good."

*The presentation order was not counterbalanced because of availability of equipment and the schedule. Temperature of the day and the fact that these participants have not trained recently with body armor may have confounding effects on the results.

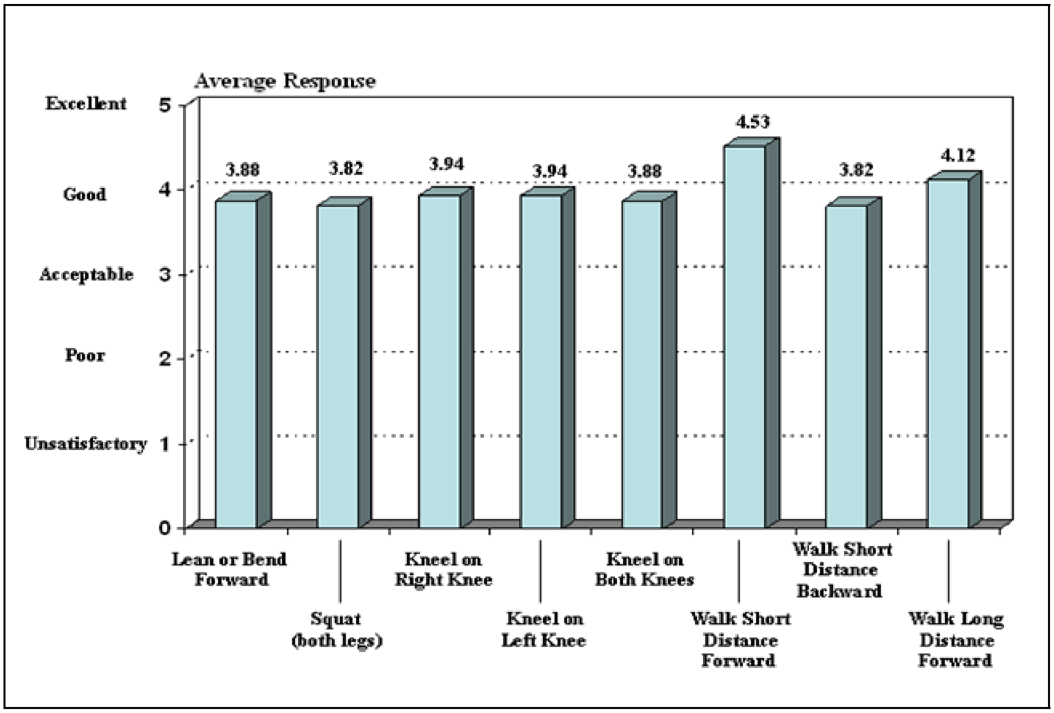

Figure 4. User feedback during static exercises.

For the obstacle course trials, a rating scale (extremely, moderately, neutral, moderately, and extremely) was used by the test participants to rate the bipolar descriptive adjectives. The mean user feedback ratings for QuadGard III for the obstacle course trials were calculated and are presented in figure 5. The participants' feedback after wearing the QuadGard III on the obstacle course showed areas of concern that affected dynamic performance. Figure 5 shows user feedback related to comfort and compatibility ratings as "moderately" uncomfortable and incompatible. Body movement categories were rated "neutral" to "moderately" restrictive. Feedback related to heat buildup and the effect of system bulk was rated from "moderately" to "extremely."

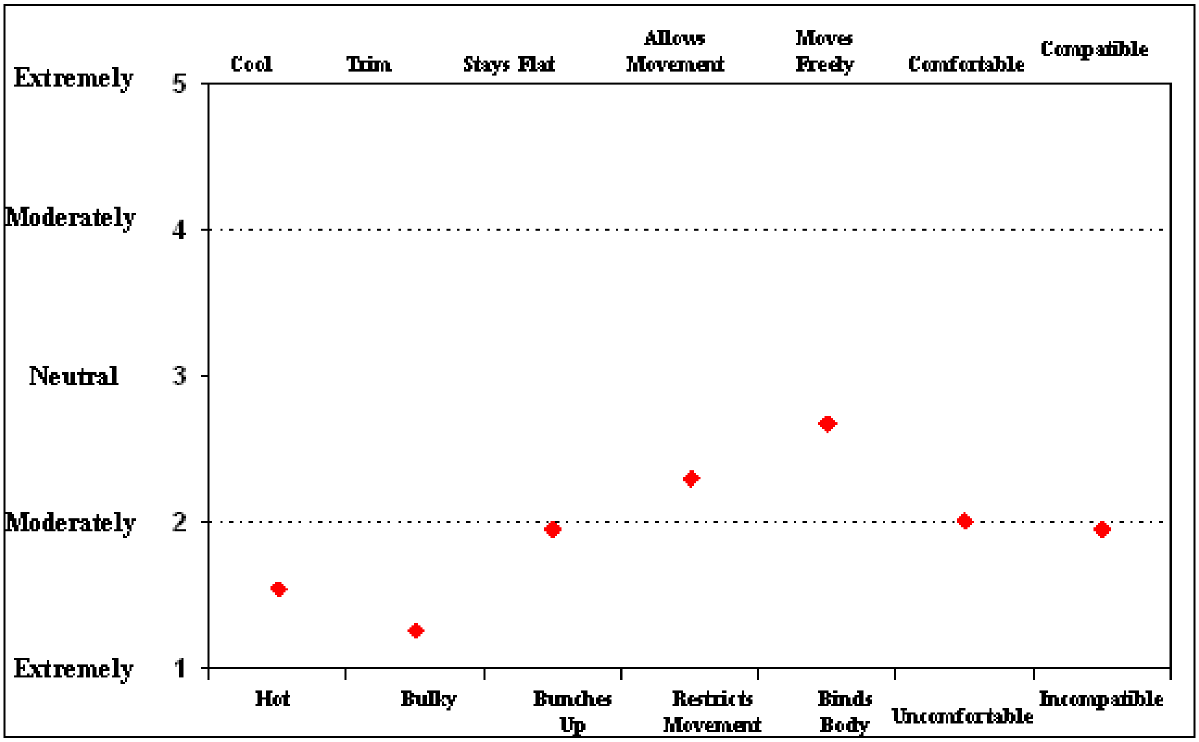

Figure 5. User feedback of QuadGard III (sleeves and trouser) during obstacle course runs.

For this evaluation there were evident user feedback differences between static exercises and obstacle course runs. The obstacle course activities, which were more strenuous and required more agility, resulted in generally negative ratings for the system compared to generally positive ratings during static exercises. The obstacle course trials required continual dynamic movement and caused potential heat buildup. The static exercises were conducted separately with time to rest between events and were less strenuous. This assessment was conducted during late April and early May in Maryland, where the temperatures were typically 70 °F or less. (These participants had not trained recently with body armor. Future user feedback should be obtained from seasoned warfighters experienced with wearing body armor and should be conducted in a warmer environment that mimics current operational conditions.)

The participants negotiated the obstacle course three times in each configuration. The mobility-portability obstacle course mean times by configuration were Baseline = 5 min, 6 s; Baseline with Vest (OTV) with QuadGard arms = 5 min, 56 s; and Baseline, OTV with QuadGard III arms and trouser = 6 min, 49 s. Wearing the QuadGard III arms with the OTV increased the weight by 11.4 lb and resulted in a 16% increase in obstacle course time over the baseline.

Similarly, wearing the QuadGard III arms and trouser with the OTV increased the weight by 18.4 lb and resulted in a 33% increase in obstacle course completion time over the baseline. The increased obstacle course times were not unexpected due to adding weight and bulk particularly to the extremities of the body. Martin (1985) showed that weight added to the thighs or feet can significantly affect the physiological workload of a person who is running.

9. Configuration Design Guidance and Recommendations

Prior to the static and obstacle course user evaluations, the original QuadGard II configuration design had been reviewed by the ARL HRED investigator during an in-house assessment. The initial design concept was based on a “chaps”-style pant or trouser with a cramp-on light duty suspender. Articulated arm segments were anchored to the OTV and supported by a single strap behind the back. The recommendations provided led to the configuration of the QuadGard III configuration: a full-length zipper on the outer edge of the trouser and an integral adjustable heavy duty suspender. These recommendations were incorporated into QuadGard III, which was then assessed via the static exercises and the obstacle course. The results of these assessments show the need to (1) reduce or eliminate the restrictions on the body in motion, (2) improve air movement between the wearer and the armor, and (3) improve the function of the configuration.

The following recommendations are listed by segment of the QuadGard III:

- Shoulder pad
    - Reshaped to eliminate OTV interference.
- Three-point OTV attachment system
    - Rear strap: modified to pass under OTV small arms protective insert pocket flap.
    - Center strap: use Velcro[*] instead of dot snap attachment.
    - Front strap: added three positions for arm length adjustment.
- Upper arm
    - Add protection to minimize frontal exposure.
    - Replace Cordura[†] with ripstop inner liner to facilitate donning/doffing.
- Lower arm
    - Increase the circumference to ease doning/doffing/movement.
    - Add a ventilation material flap along the lower edge and secure it with a Velcro strap.
    - Replace Cordura with ripstop inner liner to facilitate donning/doffing.
- Upper leg/trouser waist

[*]Velcro is a registered trademark of Velcro Industries B. V.
[†]Cordura is a registered trademark of AHH.Biz.

- Position a small Fastex[*] closure on a belt on each hip area to improve fit and allow access to pockets.
- Add a flap fold-back feature with Velcro to maintain the open/accessible position to pockets.
- Increase the circumference to ease donning/doffing/movement.
- Replace present belt buckle with a large Fastex buckle on the waist belt.
- If needed, add ballistic protection layers to outer thigh area.
- Along the outer edge of the leg, add a ventilation flap with Fastex quick release buckle.
- Modify the suspender attachments with a Fastex quick release buckle.
- To ease donning and doffing, replace Cordura with a ripstop inner liner.

• Knee
  - Increase the circumference to ease donning/doffing/movement.
  - Increase the flexibility of knee design.
  - Add an integral knee pad for comfort.

• Lower leg
  - Add a ventilation material flap along the outer edge and secure it with a Velcro strap.
  - Add Velcro tie-downs over the zipper.
  - To ease donning/doffing, replace the Cordura with a ripstop inner liner.
  - Increase the circumference to ease donning/doffing/movement.

10. Discussion/Conclusions

The QuadGard III user feedback differences between static exercises (figures 4) and obstacle course runs (figure 5) stem from the differences in physical demands required to accomplish the required tasks. The feedback related to the dynamics of the obstacle course shows the need to modify the physical configuration of the QuadGard III, thereby reducing or eliminating the restrictions on the body in motion and improving air movement between the wearer and the armor to help reduce heat buildup. The recommended modifications of the configuration should

[*]Fastex is a registered trademark of Nexus N.A.

reduce and eliminate restrictions on the body in motion, plus improve air movement between the wearer and the armor and improve the function of the next generation of QuadGard.

11. Summary

The results of this limited assessment helped guide improvements in the QuadGard design. The Joint IED Task Force, Washington, DC, in conjunction with the U.S. Army Rapid Equipping Force, planned an operational evaluation of QuadGard phase IV with the U.S. Army and Air Force.

The U.S. Marine Corps System Command initiated the pilot of QuadGard phase IV and provided funds to further the development of QuadGard phase V to meet their special operational requirements.

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Appendix. Limb Protection System Questionnaire

While wearing the limb protection system, mark your rating with an "X" in the appropriate box describing your ability to perform each task from excellent = 5, good = 4, acceptable = 3, poor = 2, unsatisfactory = 1.

	Excellent	**Good**	**Acceptable**	**Poor**	**Unsatisfactory**
Lean or bend forward	5	4	3	2	1
Squat (both legs)	5	4	3	2	1
Kneel on right knee	5	4	3	2	1
Kneel on left knee	5	4	3	2	1
Kneel on both knees	5	4	3	2	1
Walk a short distance forward	5	4	3	2	1
Walk a short distance backward	5	4	3	2	1
Walk a long distance forward	5	4	3	2	1

While moving with the limb protection system, describe your perception of the system by selecting one rating (excellent, moderately, neutral) per pair of bipolar descriptive adjectives.

	Extremely	**Moderately**	**Neutral**	**Moderately**	**Extremely**	
Hot	—	—	—	—	—	Cool
Trim	—	—	—	—	—	Bulky
Bunches up	—	—	—	—	—	Stays flat
Allows movement	—	—	—	—	—	Restricts movement
Binds body	—	—	—	—	—	Moves freely
Uncomfortable	—	—	—	—	—	Comfortable
Compatible	—	—	—	—	—	Incompatible

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