DESIGN AND DEVELOPMENT OF AN ADVANCED LOWER EXTREMITY: ALEX II

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INTRODUCTION

ALEX II represents the second generation Advanced Lower Extremity which began with the National Highway Safety Traffic Administration's (NHTSA) original version (ALEX I, hereafter referred to as ALEX) several years ago. Current efforts have been undertaken in order to make design improvements in the ALEX leg. Many of the aspects of the original ALEX have been maintained, but additional biomechanics specifications for the foot and ankle have since become available and have thus been integrated into the new ALEX II design.

The most significant aspect of the new ALEX II design lies in its flexibility to achieve any desired torque-angle ankle characteristic with relative ease. This means that as future biomechanics data regarding ankle response continues to become available, the ankle can be easily "tuned" to the desired response. This is significant since the ALEX II will not require full redesign should future data provide, or future researchers require, a different ankle response characteristic. This paper emphasizes the flexibility of the ALEX II design in this respect. The importance of the ALEX II design lies in the *technique* used to achieve ankle moment-angle response, rather than the *actual* moment-angle characteristic responses achieved, since specifications for the ankle response may well change in the future.

DESIGN REQUIREMENTS

Design specifications were determined from biomechanics data collected primarily at Renault and/or the University of Virginia. A detailed explanation of the data collection techniques and determination of these specifications are given in Crandall, et al., (1) and Portier, et al., (2). Results of the study conducted by Crandall et al., indicated that the ankle response in both flexion and inversion/eversion modes from both volunteer and cadaver subjects was continuous, with steadily increasing moment as angle increased. Figure 1 (Portier (2)) displays the continuous ankle response from cadavers and various dummy legs. This continuous specification was not reflected in any current foot/ankle designs as Figure 1 illustrates. In the ALEX II therefore, this phenomenon was treated with particular importance and, along with *flexibility* for tuning the ankle response, became the primary focus of the ankle design process.

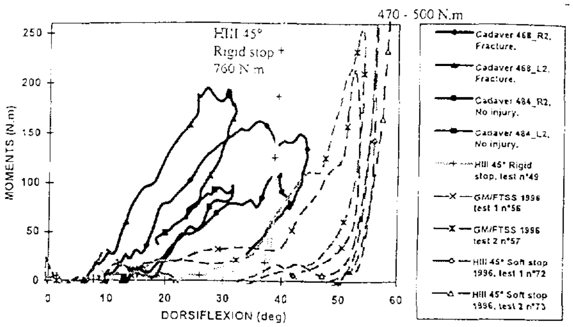

Figure 1. Dynamic dorsiflexion response using Renault impact setup for cadavers and various dummy legs (Portier et al. (2)).

Range of Motion

Many features of the original ALEX were maintained in the new ALEX II design. These include ankle rotation measurement at the ankle about the x (inversion/eversion) and y (plantarflexion/dorsiflexion) axes. In addition, the ALEX II is capable of measuring rotation about the z axis (internal/external rotation). Further, ALEX II offers a more biofidelic range of motion than ALEX in nearly all of these aspects (Table 1). Like ALEX, ALEX II utilizes separate axes for plantarflexion/dorsiflexion and inversion/eversion movement.

Table 1.
Range of motion comparison between ALEX and ALEX II

Range of Motion	Original ALEX	ALEX II	ALEX II Critical Moments at Max Angle ROM
Plantarflexion	38°	55°	25 Nm
Dorsiflexion	43°	45°	140 - 325 Nm
Inversion	19°	32.5°	27 Nm
Eversion	19°	32.5°	29 Nm
Internal Rotation	Not Available	22.5°	Not Available
External Rotation	Not Available	22.5°	Not Available

Achilles Tendon

In addition to the continuous moment-angle requirement of the ALEX II, an "Achilles tendon" element was incorporated into the design. The purpose of the Achilles element was to more realistically represent the compression forces in the tibia. Also, recent research into the importance of the Achilles tendon indicates that the tendon is capable of generating high forces during a panic braking scenario (Manning (3)). Although the ALEX II Achilles tendon was designed utilizing passive data, active tendon response might then be simulated in future studies with the ALEX II by pre-loading the brake pedal utilizing the Achilles.

Center of Rotation Heights

The centers of rotation for flexion, as well as inversion/eversion as recommended by Crandall et al.(1) is given in Table 2. The pivot location for the ALEX II was based on these findings.

Table 2.
Center of Rotation Heights from the Bottom of the Foot (Crandall (1))

Center of Rotation	Joint Height (mm)
Dorsiflexion Plantarflexion	76 +/- 8
Inversion Eversion	71 +/- 12

Center of Pressure and Foot Compression

ALEX II incorporates biofidelic center of pressure and foot compression characteristics as specified in the 45° Hybrid III foot. The ALEX II has an increased distance (compared to ALEX I) from the center of ankle to heel distance. The distance was increased from 19.0 mm to 28.2 mm (anatomic average was 28.2 +/- 6.35mm). This recommendation to increase center of ankle to heel distance from 19.0 mm to 28.2 mm was based on pressure point of the heel using pressure sensitive FUJI film paper on six volunteers (Crandall (1)). The ankle to heel distance of 28 +/- 6 mm is also currently specified for the Hybrid III 45° foot. The ALEX II design also has the 28 mm ankle to heel distance.

The center of pressure location at the ball of the foot for the new Hybrid III 45° foot was determined as 123 +/- 6 mm from the ball of the foot to the ankle joint. The ALEX II design also incorporates a distance of 123 +/- 6 mm from the ball of the foot to the ankle joint.

Dorsiflexion Characteristics

The dorsiflexion requirement (Figure 2) was derived (Kuppa (4)) from data collected by Portier, et al. (2) from dynamic cadaver test data. As stated previously, Figure 1 illustrates the continuous response characteristic of the ankle which became the primary focus of the design study. It should be noted that the test setup used by Renault to collect the data in Figure 1 utilized a spring-damper linear impactor system. In addition, the cadaver was supine with femur extended vertically and tibia horizontal for the impacts. This

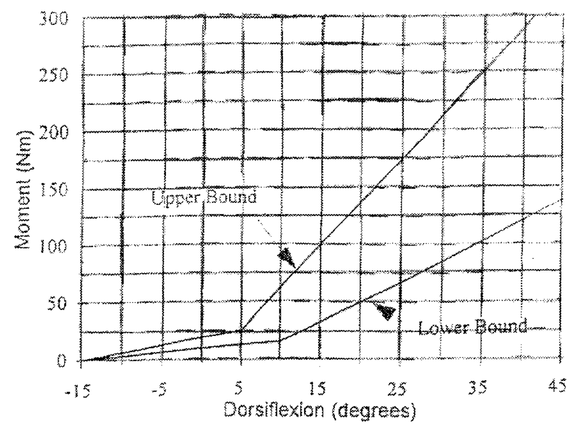

Figure 2. Dynamic moment-angle characteristic specification corridor (Kuppa (4)) for ALEX II leg based on Renault (Portier (2)) cadaver data seen in Figure 1.

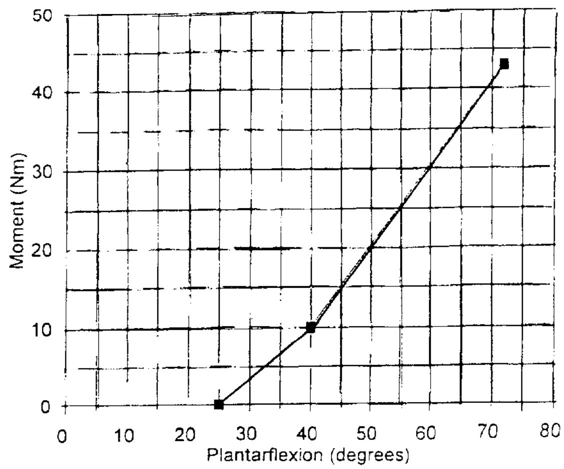

Figure 3. Joint response in plantarflexion design specification for the ALEX II utilizing Paranteau (5) data.

meant that the impact at the ball of the foot created not only a dorsiflexion response at the ankle, but also rotation at the knee and hip joints. These corridors are specific to the particular test setup at Renault and comparisons pertain *only* in similar test conditions.

Plantarflexion Characteristics

Quasi-static tests were conducted by Paranteau (5) to determine the moment angle characteristics of the ankle joint using human cadaver lower legs excised at the distal tibia-fibula. There was no passive response from musculature in these tests since the muscles of the anterior crural compartment (which resist plantarflexion) had been severed. Therefore, the moment angle curves represent only the response at the ankle joint.

UVA conducted quasi-static volunteer tests to determine plantarflexion moment-angle curves. The test setup was the same as that used for the volunteer dorsiflexion tests. The volunteers were told to relax their muscles during the test. This data shows much higher rotational stiffness in plantarflexion than Paranteau's data. This could be due to passive and active muscle response of the volunteers in the UVA tests. UVA tests do suggest that there is zero moment up to 25° of plantarflexion. The design specifications for ALEX II shown in Figure 3 for plantarflexion utilize Paranteau's test data with a zero level up to 25°.

Inversion Characteristics

Quasi-static moment-angle responses in inversion were obtained from tests conducted at Renault using cadaveric subjects. Figure 4 (Crandall (1)) shows quasi-static inversion data from cadaveric subjects from which the target specification for ALEX II was derived (Figure 5).

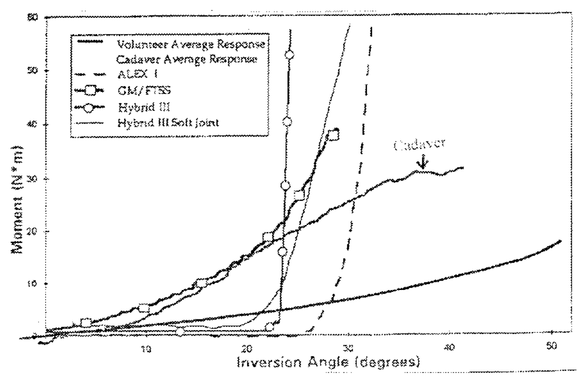

Figure 4. Quasi-static average moment-angle responses from volunteers, cadavers, and various dummy legs in inversion (Crandall (1)).

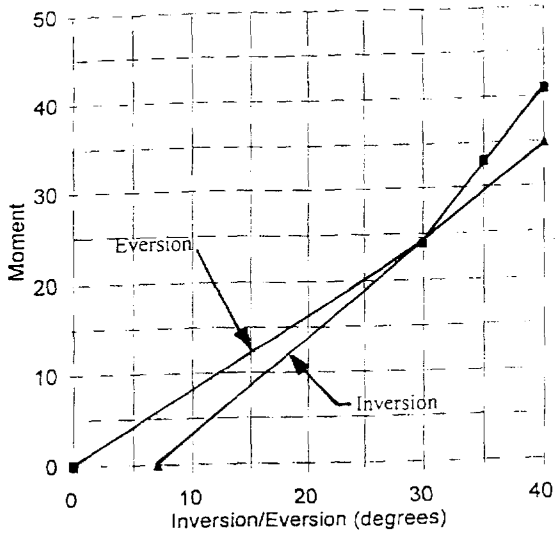

Figure 5. Quasi-static moment-angle specifications for the ALEX II leg in inversion and eversion.

Eversion Characteristics

Quasi-static moment-angle responses in eversion were obtained from tests conducted at Renault using cadaveric subjects and at UVA using volunteers (Figure 6, Crandall(1)). The results from both labs are very similar. The moment-angle curve in eversion from UVA was used for the ALEX II design (Figure 5).

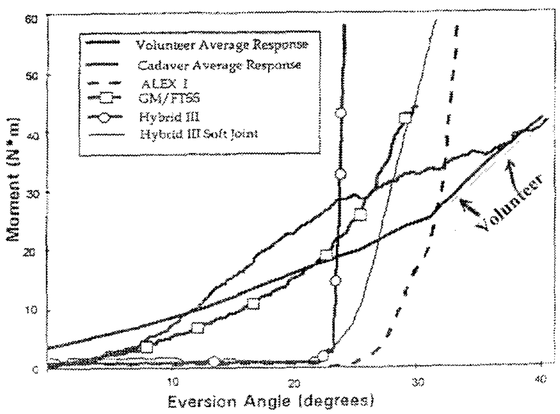

Figure 6. Quasi-static average moment-angle responses from volunteers, cadavers, and various dummy legs in eversion (Crandall (1)).

IMPLEMENTATION DESIGN

Figures 7 and 8 show the design of the ALEX II and illustrate the various features implemented in the ALEX II leg. The location of ALEX II sensors are noted in the figures. Figure 9 is a photograph of the leg. The ALEX II leg is capable of measuring 22 channels of data. These measurements are shown in Table 3. The ALEX II total weight was 5.29 kg. Subassembly weights are given in Table 4.

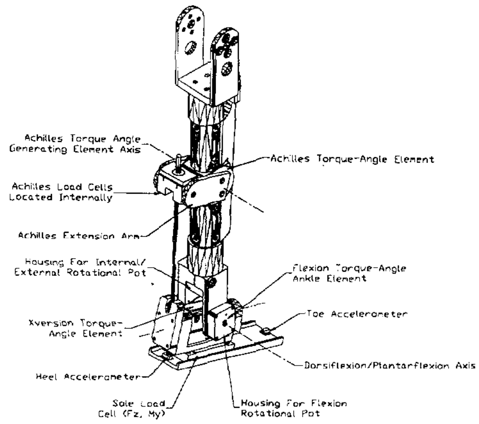

Figure 7. ALEX II leg (oblique view) shown with Achilles tendon and various features.

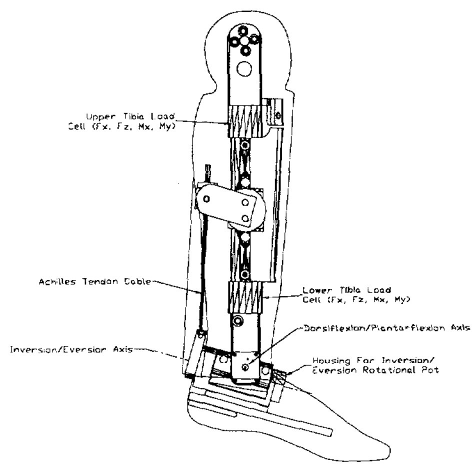

Figure 8. ALEX II leg (side view) shown with Achilles tendon and various features.

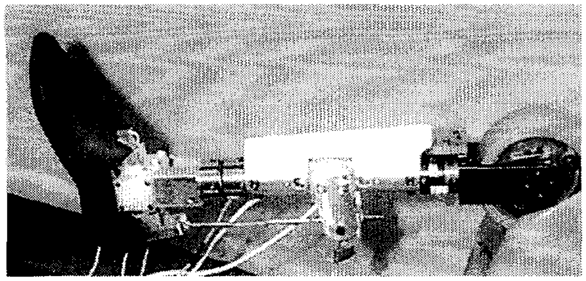

Figure 9. Photo of ALEX II.

Table 3.
ALEX II data channels.

ALEX II Area of Measurement	Measurement (Ang = Angle, F = Force, M = Moment, A = Acceleration)
Ankle	Ang_x Ang_y Ang_z
Femur	F_x F_y F_z M_x M_y M_z
Upper Tibia	F_x F_z M_x M_y
Lower Tibia	F_x F_z M_x M_y
Toe	A_z
Heel	A_z
Achilles Tendon	F_z
Sole of Foot*	F_z M_y

* Not yet available. Provisions are made in the design to include these load cells upon availability.

Table 4.
Weight characteristics of the ALEX II leg

Component	Weight (kg)
Lower leg including foot	3.99
Foot only	1.24
Total lower leg weight	5.23

The proximal and distal ends of the tibia for the original ALEX, as well as Hybrid III, provided axial and shear loads at an angle to the anatomical axis. Therefore, the ALEX II design implements a straight tibia shaft with the location of the knee and ankle attachments moved accordingly. In the current Hybrid III leg, a compressive force introduces a moment due to angles at the proximal and distal ends of the tibia. A straight tibia would eliminate these moment artifacts. The ALEX II design incorporates an oblong shaped and tapered tibia bone in order to place the anterior tibia bone in the same position as the Hybrid III relative to the anterior tibia flesh while eliminating the angles at the proximal and distal ends of the tibia shaft. The Hybrid III knee casting design was maintained since the knee slider mechanism has been recently improved by Applied Safety Technology Corporation (ASTC (6)) with a ball slider mechanism, currently available for the Hybrid III.

The ALEX II design allows ankle rotation and measurement about all 3 axes (X, Y, and Z) and includes more biofidelic ranges of motion and stops (Table 1). Bumpers with characteristics similar to the Hybrid III ankle bumpers are utilized at the joint stops to prevent metal-to-metal contact. The ankle angles are critical measurements since the ankle design is specified by a moment-angle characteristic. It is therefore not only necessary to determine moment characteristics, but also at *what angle* these moments occur. The rotation measurements are made by three Tocos (7) (model GF12)) rotary potentiometers. These devices are small potentiometers which are installed on the ALEX II heel (X rotation measurement), at the medial malleolus (Y rotation measurement), and distal to the lower tibia load cell (Z rotation) (Figures 7 and 8).

The ankle rotation was achieved by a separate axes joint design with orthogonal axes. The moment-angle specification for the ankle indicates continuous loading with increasing resistance for all ankle motions (Figure 1). The mechanism which achieves this response is described below. The ALEX II was designed with the flexibility to permit *any* desired moment angle characteristic to be achieved, should these specifications be revised in the future as new data becomes available.

Continuous Torque

Ankle Joints - Various methods were investigated to achieve the required torque-angle characteristics of the design specifications. Since the specifications required a continuous torque-angle response with a progressively increasing torque, an isolation damper device was utilized. The design began with an off-the-shelf isolation damper manufactured by Rosta Company (8) which could then be easily modified to meet *any* desired torque-angle characteristic. This particular type of damper assembly is commonly used on small cars and trailers outside the United States as a vibration dampening suspension mount. This device (shown schematically in Figure 10) consists of a rigid external housing into which four cylindrical rubber elements and a square center shaft are inserted. When the center shaft is rotated, the cylindrical elements compress and generate a continuous torque-angle response. The rubber elements can easily be "tuned" in a number of ways to elicit any desired torque-angle response. For example, changing the length of the rubber cylinder elements, the durometer or type of rubber, the shape of the elements, or shape of the center shaft all affect the response. Therefore, this method of generating the desired specification is appealing since the ankle can be "tuned" as desired as new biomechanics data becomes available.

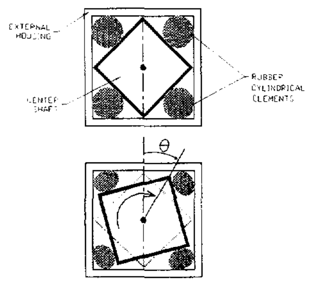

Figure 10. Cross section of torque-angle element (Rosta (8)) used in ALEX II ankle and Achilles tendon. Top Figure illustrates zero torque-angle. Bottom Figure shows compression of rubber elements to generate torque when a rotation is applied to the center shaft.

Figure 11 shows various torque-angle elements which were "tuned" to exhibit several responses by changing the length of the rubber cylindrical elements. These curves illustrate the ability of the design to achieve any number of desired responses by changing the rubber elements. The design is extremely flexible in that respect.

The torque-angle method described above was utilized at both the ankle and the Achilles tendon. For the ankle, two torque-angle elements were positioned perpendicularly (Figures 7 and 8) for generating the desired responses in both dorsiflexion/plantarflexion and inversion/eversion modes. At the ankle, the center shaft of the torque-angle element was rotated at a 15° initial position in plantarflexion to simulate the "natural" position of the foot, the point at which torque on the ankle is zero.

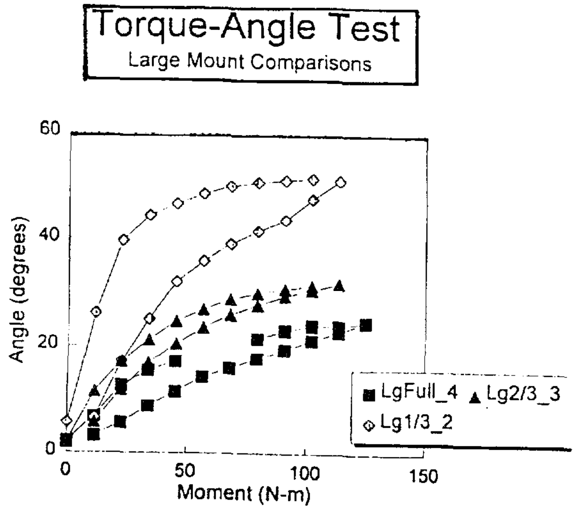

Figure 11. Moment-angle responses of several modified isolation damper elements. Devices were modified by varying the length of the rubber cylindrical elements seen in Figure 10. Responses indicate the flexibility of the design to easily achieve any desired moment-angle characteristic.

Figure 12 shows results from a dynamic test with the moment generating element installed in the ALEX II leg at the Achilles tendon and at the ankle. The corridors shown represent design corridors based on data collected by Portier et.al. (2). However, these design corridors were derived from the Renault test setup described by Portier et.al. (2) which utilized a spring-damper linear impactor system. In addition, the cadaver was supine with femur extended vertically and tibia horizontal for the impacts. This meant that the impact at the ball of the foot created not only a dorsiflexion response at the ankle, but also rotation at the knee and hip joints.

Since it was not possible to achieve the same test setup and test the ALEX II leg in that particular configuration prior to publication of this paper, another type of dynamic test was conducted. In that setup (Figure 13) the ALEX II tibia was rigidly mounted in a horizontal position proximal to the upper tibia load cell (no knee and hip were utilized). A linear pendulum with a representation of a pedal was initially positioned against the ball of the foot. The foot was then impacted from rest to achieve a dorsiflexion response. Since the two test configurations differ, the corridors cannot be *directly* applied to this impact test. However, these results *do* illustrate the ability of the ALEX II to perform dynamically. Since the ALEX II design is extremely flexible with respect to the moment

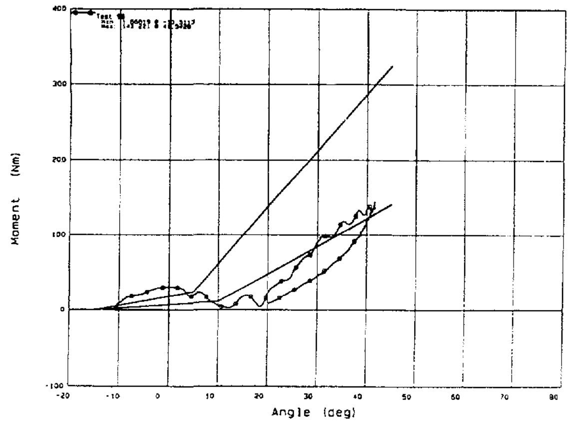

Figure 12. Dynamic dorsiflexion response of the ALEX II achieved from the rigidly mounted tibia test setup. Design corridors indicate the Renault test specification corridor (Figure 2). Although the two tests differ in setup and the corridor cannot be *directly* compared to the data, the rigid-mount test provides an indication of the ability of the ALEX II leg to perform dynamically.

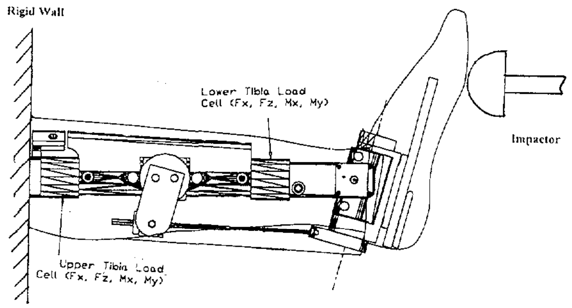

Figure 13. Setup for dynamically testing the ALEX II in dorsiflexion by rigidly mounting the tibia. Results for this type of test are indicated in Figure 12.

generating device in the ankle, the ALEX II can be easily "tuned" to fall within the corridor shown in Figures 2 and 12 when the Renault test setup is eventually available for test; at that time, a *direct* comparison can be made between ALEX II response and design specifications.

Inversion/eversion torque-angle response was generated quasi-statically, rather than dynamically, by the perpendicular torque-angle element at the ankle only, without influence of the Achilles tendon cable. The ALEX II results for inversion/eversion are illustrated in Figure 14. Since the moment generating element for inversion/eversion for the ALEX II is symmetrical, these results represent *both* inversion and

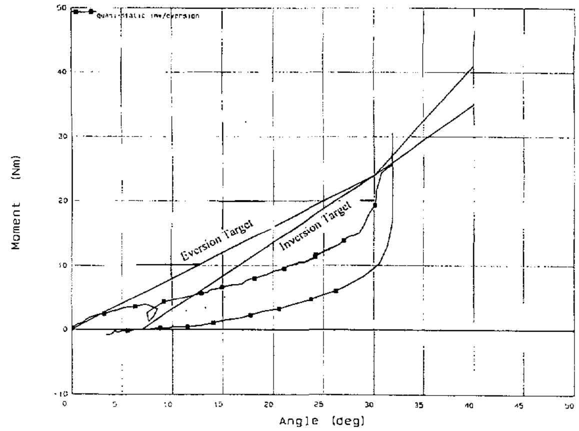

Figure 14. Quasi-static inversion/eversion results for the ALEX II compared to target specifications. ALEX II responds the same in inversion and eversion due to symmetry of the joint.

eversion response. Again, the ALEX II design could very simply be "tuned" by modifying the size, shape or stiffness of the rubber cylindrical elements (Figure 10) should the current ALEX II response need to be adjusted.

Achilles Tendon - Early versions of the ALEX II had the full moment response built entirely into the ankle joint. However, for more realistic Fz loads, this was later changed to incorporate a tendon and the torque at the ankle joint was softened. Choice as to the presence of the Achilles or incorporating the moment characteristics entirely into the ankle depends on the accuracy of tibia compression loads desired, since the Achilles tendon increases such loads and changes moment in the tibia. Since the Tibia Index calculation utilizes the resultant moment and compressive (Fz) force, the Tibia Index calculation would require revision due to the presence of the Achilles tendon. At a system level however, the response of the foot and ankle would be the same; the stiffness between the foot and leg remains unchanged in either of the two design configurations, with or without an Achilles tendon.

The current ALEX II has been designed with an "Achilles tendon" element. This element consists of a steel cable (7x19, 3mm diameter) with swedge welds at each end. An "eyebolt-like" element was swedge-welded to the distal end of the Achilles cable; the cable was attached to heel with a bolt through this hole. This prevents the tendon from binding during flexion events. The proximal end contains a threaded portion to allow for lengthening or shortening the Achilles tendon so that the initial position of the foot can be changed if desired. The Achilles cable was approximately 20 cm in length. It was attached to the tibia approximately 20.8 cm distal to the center of rotation of the knee joint (21 cm proximal to the center of rotation of the dorsiflexion axis). A Sensotec (9) "button" load cell (model LFH-7I/280-10) was utilized to measure Achilles tendon forces.

The torque-angle method described above was also utilized at the Achilles tendon. For the Achilles tendon, a torque-angle element was inserted into the tibia near the upper portion of the tibia shaft below the lower tibia load cell (Figures 7 and 8). In order to generate torque-angle from the Achilles cable, a small extension "arm" attached to the center shaft of the torque-angle element was utilized. The proximal end of the Achilles cable was fixed to the end of the arm while the distal end of the cable was attached to the back of the heel. The resulting design allowed the cable to rotate the torque-generating element thus placing the cable in tension during dorsiflexion and generating an increasing resistance. In addition to torque generated through the Achilles element, moment was also produced at the ankle joint as explained above. Conversely, during plantarflexion, the Achilles cable remained slack and torque was generated only by the torque-angle element at the ankle joint.

CONCLUSIONS

ALEX II Design Summary

The following is a summary of the major features incorporated into the ALEX II design.

- Ankle rotation and measurement about all 3 axes (X, Y, and Z)
- More biofidelic ranges of motion and stops:
    - 45° dorsiflexion
    - 55° plantarflexion
    - 32.5° inversion
    - 32.5° eversion
    - 22.5° internal rotation
    - 22.5° external rotation
- Continuous loading with increasing resistance for all ankle motions
- Separate joints with orthogonal axes
- Optional "Achilles tendon" element
- Ankle height for dorsiflexion/plantarflexion: 76 +/- 8mm from bottom of foot
- Ankle height for inversion/eversion: 71 +/- 12mm from bottom of foot
- Ankle to heel distance: 28 mm
- Ankle to ball of foot distance: 123 mm
- Weight of lower leg including foot: 5.23 kg
- Weight of foot: 1.24 kg
- Weight of tibia (lower leg, excluding foot): 3.99 kg
- Utilize current (Hybrid III 45° foot) center of pressure and foot compression data in foot design
- Removal of proximal and distal tibia angles so that tibia load cells are on the center line between the knee and ankle pivots
- Ball knee slider

ALEX II Data Channel Summary

The ALEX II leg design utilizes the following data channels:

- Femur forces and moments
- Upper and lower tibia forces and moments (Fx, Mx, My, Fz)
- Ankle angle for all three axes
- Toe and Heel acceleration (z)
- "Achilles tendon" load
- Provisions for a load cell to measure force and moment of the sole of the foot (Fz, My)

SUMMARY

The ALEX II foot and ankle represents the next generation Advanced Lower Extremity. It incorporates various new design aspects based on newly obtained biomechanics data. Among the most significant changes in the design is the inclusion of an Achilles tendon device. In addition, major efforts in the design process were focused on the implementation of a continuous moment-angle response device at both the ankle joint and Achilles tendon element. These elements have been shown to be easily tuned and have been designed to give any desired response characteristics in plantarflexion/dorsiflexion and inversion/eversion. The technique utilized to achieve the continuous torque-angle characteristic of the ankle was emphasized, rather than adherence of the results to specific design corridors. This aspect of the design means that the ALEX II can be easily modified to achieve *any* desired response as future data becomes available. Further development of the ALEX II leg would include fine "tuning"the responses for current and future biomechanics data. This would entail validation of the dorsiflexion response in a Renault-type fixture which was utilized for specification of the dorsiflexion ankle response. Additional future studies might also entail the possibility of utilizing the Achilles tendon element to simulate active braking.

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