Technical Note: On the Design of Manually Adjustable Ankle Units for Variable Terrain
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Abstract

This paper provides details on the design of adjustable ankle units for transfemoral and transradial prosthetic devices. The design was intended to enable the user to quickly adjust the flexion of a prosthetic foot in sub-freezing temperatures, where donning and doffing clothing and the prosthesis presents a significant obstacle. The units must also be able to tolerate significant abuse, cold, ice, and water while maintaining their function. Additionally the unit must be attached using standard pylon or fittings, and must be short enough to fit in the existing pylon space, so no modification to the users socket or prosthetic foot is required. This paper presents two potential solutions to the proposed problem, one with continuous adjustment using a friction fitting, and one with discrete positioning using a geared coupling. A finite element analysis of the design was performed to determine the suitability of design material and dimensions. The proposed friction fitting was found to have greater potential, but benefits of other methods are discussed as well. Future work will focus on failure testing of prototype devices, followed by in-use field testing by highly active amputee subjects.

Background

Passive ankle prostheses generally do not include features for large adjustments to ankle flexion angles. Some ankle units do allow for variation of plantar flexion to accommodate shoes of varying heel height, but are not designed for use with large angles of dorsiflexion for hill assent. Hansen et al. have studied the path of center of pressure relative to the shank, called the roll-over shape, of able-bodied individuals ascending and descending 0°, 5° and 10° ramps. They found that the best fitting rotation of level ground roll-over shape corresponded with the angle of incline of the ramp for positive inclines of the ankle-foot roll-over shape, and for positive and
negative inclines of the knee-ankle-foot roll over shape.\textsuperscript{1} Therefore, the ability to accommodate the sagittal angle of the ankle to approximate the ground slope is of importance.

People may routinely encounter sloped terrain in daily life.\textsuperscript{2} For instance, driveways are commonly sloped as are wheelchair accessible ramps used to access buildings and homes. In the United States, the Americans with Disabilities Act of 1990 (ADA) provides regulations with respect to slopes to determine what is compliant. For instance, building access ramps should be approximately 5° to be considered in compliance for new construction.\textsuperscript{3} Microprocessor foot/ankle systems are beginning to emerge that boast the ability to accommodate ground slope with the goal of minimizing the effort and skin stresses imposed on the amputee when traversing these terrain conditions.\textsuperscript{4,5} Specialized activities such as construction work, military service and emergency response may require ambulation on sloped terrain in a loaded condition. Traditional components may be inadequate to sustain the hostile terrain, as they are typically design and tested for walking on level ground, stairs, or slight inclines. Mountaineering, which may be occupational or recreational, may require ambulation on extreme slopes under heavily loaded conditions.\textsuperscript{6} The purpose of this technical note is to describe early designs of ankle systems conceptualized to accommodate extreme ground slopes under rigorous loading.

**Design 1: Friction Adjustment**

This design has the primary advantage of offering continuous adjustment, allowing the user to set the flexion angle to any position that they desire, within the usable range of the device. Resistance to flexion is adjusted by a cam lever, similar to the adjustments found on bicycle wheel quick disconnects. The disadvantage of this design is the relative difficulty in selecting the appropriate amount of pressure that the cam level should apply to the fitting. If the cam is adjusted too tightly it will be difficult to adjust, and if it is too loose the joint may move during
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walking. The proposed design uses 6061 aluminum for the connector pieces and stainless steel for the bolt, nut and cam lever. The connectors can be cut and welded from aluminum plate, and the cam lever ordered from bicycle part suppliers, cut to length and threaded. A rendering of the design is shown in Figure 1a.

![Figure 1a](image1.png) ![Figure 1b](image2.png)

**Figure 1. (a) Friction adjustment design. (b) Geared coupling design.**

**Design 2: Geared Coupling**

This design, shown in Figure 1b, uses a compliant lever to apply pressure to a gear coupling that locks the ankle unit in place. By applying sufficient pressure to the lever, the gear coupling separates allowing the unit to be set into a new position. Since the gears can only mesh in a discrete number of positions, a limited number of adjustments can be achieved by this design. The current design allows for 5 different positions, 0°, ±8°, and ±16°. These angles allow the use of a stock and gear and pinion, and adjustment for moderate and heavy inclines. This can be adjusted by changing the pitch of the teeth used in the gear, but smaller angles will result in weaker teeth, and a higher potential for failure during loading.
Stress analysis of designs

Stress analysis was performed in Solidworks 2011 Simulation (Dassault Systems, Vélizy-Villacoublay, France). A static bearing load of 2000N was applied to each section of the couplings. The friction coupling had a lower maximum von Mises stress of 79MPa. The top and bottom portions of the geared coupling had maximum stresses of 93MPa and 99MPa respectively. These stresses fall well under the yield stress of tempered (T6) 6061 aluminum, but are near the yield stress of the weaker tempered and annealed (T1 & O) aluminums with typical yield strengths of 241MPa and 97MPa respectively. Since these pieces would likely be welded together from milled plates, the lower strength tempers should be used for a conservative estimate. Rendering of stress distribution in the parts are given in Figure 2.

![Figure 2. Rendering of stress distribution.](image)

Discussion

These designs present potential solutions to the need for rugged manually adjustable ankle prostheses. Performance is expected to be similar to that of commercially available devices when properly adjusted. Aluminum alloys selected resist corrosion and do not experience temperature embrittlement, making the devices tolerant to cold, water, and ice. Future work will focus on physical failure testing of prototype devices, as well as general test of device function, forum factor, and ease of use. It may be necessary to re-temper the parts after fabrication which would
increase their cost. Of the two designs considered the friction coupling shows greater promise, with the lower maximum stress and greater range of adjustability. Future work will focus on fabrication and testing of prototype devices. This device could also be used to rapidly test the effect of ankle flexion angle in prostheses during hill assent and descent. The dimensions for the friction coupling unit are given in Figure 3. The unit can be constructed from a 1/8” thick sheet of 6061 aluminum, cut and milled to size, and then welded in place. The friction cam can be made by cutting and threading a bicycle quick release skewer. The center hole diameter should be adjusted to fit the diameter of quick release used (common sizes are 8mm, 10mm, 5/16”, and 3/8”).

![Figure 3. Dimensions for friction coupling unit.](image)

In addition to these new prosthetic ankle designs, simpler solutions have been discussed to address changing sagittal foot alignment to ease amputee ambulation on sloped terrain under strenuous (i.e. loaded) conditions. For instance, traditional hex screws could be replaced with wing screws, as shown in Figure 4, to facilitate quick interchange between pre-aligned feet/pylon systems when only one prolonged slope is planned. This would require carrying an additional foot/pylon system that is pre-aligned as opposed to having one system with more moving parts.
that is multi-slope adjustable as in the proposed conceptual designs. One advantage to this scenario is that a foot exchange could be managed while wearing gloves to protect the hands in freezing mountaineering conditions.

One final option is to consider using an angled tube clamp adapter. Tube clamp adapters are routinely aligned straight such that the pylon aligns somewhat in parallel with the long-axis of the prosthetic socket. However as in the previous example, changing from somewhat flat ground to a prolonged, constant slope could also be performed by changing to a pre-aligned system accommodated to the ground conditions by way of an angular tube clamp adapter. Ideally, either of the proposed solutions would minimize stump skin pressure and ease the burden of ambulation for a prosthesis user during prolonged slope conditions.

**Conclusions**

The designs presented in this paper are feasible units and ideas that would allow the adjustment of ankle flexion for extended hill ascent and descent in amputees. All of the proposed solutions are low cost relative to microprocessor foot/ankle systems that may lack the durability to withstand rigorous environments and loads. Additionally, the proposed solutions are completely
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Mechanical in nature and therefore do not require battery recharging and are at lower risk of damage from being wet. The friction coupling shows greater promise, based on the analysis of stress and function, and should be considered in future development.

References


