Adapting isokinetic dynamometry to accommodate transradial amputation: The development of a new dynamometer attachment and user case study

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Adapting isokinetic dynamometry to accommodate transradial amputation: The development of a new dynamometer attachment and user case study

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Abstract: Upper limb amputations can significantly impact daily functions and affect quality of life. Significant advances over the last few decades have resulted in lighter and stronger artificial limbs; however, users have indicated that improved function and control strategies are desirable to become more in line with able-bodied limb function. The complexity of the amputated limb muscle physiology makes quantitative clinical assessment challenging. In addition, most clinical research has focused on studying isometric (stationary) limb movements. In order to develop more robust systems, it is critical to study muscle mechanics of those with amputations under dynamic (moving) movements. One method of safely examining dynamic movements is the use of isokinetic dynamometers. These machines allow measurement of upper and lower extremity isokinetic movements at controlled angular velocities while ensuring no stress is placed on the individual (even if the participant is unable to move the lever arm). For able-bodied participants, this doesn’t present a problem. However, there is currently no commercially
available isokinetic dynamometer adapter for prosthesis users. The purpose of this project was to develop an adapter for those with amputations to safely and effectively operate the dynamometer. The adapter was tested by one clinical patient to determine its effectiveness.

**Subjects:** Bioscience; Engineering & Technology; Assistive Technology; Medicine, Dentistry, Nursing & Allied Health; Assistive Technology

**Keywords:** isokinetic dynamometry; transradial amputation; rehabilitation; strength testing

1. Introduction
The loss of a limb can diminish an individual’s ability to perform everyday activities (Kuiken et al., 2009). Amputation prevalence rates have been difficult to estimate worldwide, as many countries do not keep records (Esquenazi, 2004). However, the National Limb Loss Information Centre has estimated 1.7 million United States residents live with an amputation (one in every 200 individuals suffers from limb loss). Their 2010 annual report stated 507 individuals lost a limb per day in the United States and that number is expected to double by the year 2050 (Amputee Coalition of America, 2012). Over the past 20 years, 82% of new amputations have emerged as a result of the aging population and increasing prevalence of vascular disease (Olefsky, 2001; Ritchie & Connell, 2007). Additionally, trauma and cancer related amputations have decreased because of advancements in technology; whereas the prevalence of congenital amputations has remained fairly consistent (Amputee Coalition of America, 2012; Hsu & Cohen, 2013; Nielsen, 2002).

Lower limb amputations have been shown to occur three times more often than upper limb amputations and are commonly linked to vascular disorders. However, trauma-related and congenital amputations occur more frequently in the upper limbs (Amputee Coalition of America, 2012; Esquenazi & Meier, 1996) with 57 percent of upper limb amputations occurring below the elbow (transradial).

An amputation drastically changes an individual’s life and can create numerous physical and psychological barriers. Mobility becomes a daily challenge and individuals must learn to adapt (Horgan & MacLachlan, 2004). Everyday activities such as getting dressed, cooking dinner, and participating in leisure activities becomes increasingly difficult as the amputation level increases.

Prostheses are often prescribed to help reduce negative feelings or aid with the physical deficits an individual acquires from his or her amputation. Many different types of prostheses are available and all pose a variety of advantages and disadvantages. Myoelectric prostheses are widely studied as researchers have shown them to have the greatest potential to improve an amputee’s quality of life (Miller et al., 2008; Scheme & Englehart, 2011). However, a number of areas remain in need of further study.

While there have been significant advances in the materials used to build prostheses over the last several decades resulting in lighter and stronger artificial limbs, users have indicated that improved function and control strategies are desirable to become more in line with able-bodied limb function. Quantitative clinical assessment has been challenging due to the complexity of the muscle physiology of those with amputations. It is important to examine muscle function in prosthesis users in both the residual and intact limb to better understand mobility. One of the challenges of studying muscle function with prosthesis users is the ability to use standard muscle function devices to examine parameters such as muscle force. Furthermore, it is critical that muscle function is examined under both static and dynamic conditions to improve mobility. Davidson (2004) observed that there were no measures or devices available to specifically evaluate the functional ability of those with upper limb amputations. However, while there are few devices...
commercially available to obtain such measurements, it is precisely these devices that will in the development, understanding and research in the field of prosthetics (Davidson, 2004; Hermansson, Fisher, Bernpång, & Eliasson, 2005; Raad, 2012; Wright, 2009).

Wright (2009) examined the available measures for upper limb amputees between the years of 1970 to 2004. Several surveys have been shown to measure physical function of the upper limb including the Disability of the Arm, Shoulder and Hand (DASH) scale (Davidson, 2004) and the Prosthetic Upper Extremity Function Index. The DASH assessment tool is a 30-item, self-report questionnaire for measuring physical function and symptoms for anyone with several musculoskeletal disorders of the upper limb. The Southampton Hand Assessment Procedure (SHAP) is an observational assessment, which determines the effectiveness of a terminal device with respect to unilateral prosthetic hand functions. Other measures include the Revised Upper Extremity Functional Status module of the Orthotics and Prosthetics User Survey which includes questions pertaining to an individual’s performance of 23 self-care and instrumental upper limb-based daily living skills. Each skill is then rated according to difficulty on a scale of 1 to 5.

Other tools used to assess physical function are hand held myometry and dynamometry (Raad, 2012). These tools require one to hold a portable hand-held dynamometer in order to quantitatively and objectively assess muscular strength. The data collection is compared to unaffected muscles and matched age norms. The myometer is held at a set distance from the joint and perpendicular to the muscle being tested. No amputees are said to have been tested with it according to this database. The ambulatory accelerometry technique (Schasfoort, Bussman, Martens, & Stam, 2006) allows objective measurements of aspects of daily human behavior. This technique consists of acceleration sensors along with EMG electrodes placed on the lower arms, hands, trunk, and leg to allow the collection of data.

Apart from hand held dynamometry and myometry, and the ambulatory accelerometry technique most other tests require surveying of the subject and patient. In the research field there is, to date, no device available to measure trans-radial amputees muscle activity involved in elbow motions under controlled dynamic conditions.

One method of safely examining dynamic movements is the use of isokinetic dynamometers (Figure 1). These machines allow measurement of upper and lower extremity isokinetic movements at controlled angular velocities while ensuring no stress is placed on the individual (even if the participant is unable to move the lever arm). These devices are popular in rehabilitative medicine (Osternig, 1986) and can provide information regarding dynamic muscle contractions. Isokinetic dynamometers are considered the gold standard method to measure produced joint torque⁵. With an isokinetic dynamometer, a maximal contraction can be performed in a safe and dynamic environment where a specific angular velocity and resistance can be selected (de Araujo Ribeiro Alvares et al., 2015). The accommodating resistance of these machines and the ability to analyze muscle force presents opportunity to examine muscle function safely for clinical populations (Baltzopoulos & Brodie, 1989). Currently there are several brands of isokinetic dynamometers, however the machines are limited for use with able-bodied participants, i.e. those with intact limbs. Currently no commercially available isokinetic dynamometer adapter for prosthesis users to take advantage of isokinetic technology. Ideally, prosthesis users would be able to use this technology with and without their prosthetic limb.

The purpose of this project was to develop an adapter that can be used by those with amputations to safely and effectively operate an isokinetic dynamometer. While isokinetic dynamometers can be used to study a variety of movements in both upper and lower limbs, the tool that was designed was specific for individuals with trans-radial upper limb amputations and was intended to accommodate the residual limb with or without the prosthesis attached. The tool that was developed connects to the arm of the dynamometer and is adjustable for different prosthesis
users with varying residual limb length. One participant was presented with the adapter and asked to produce a series of contractions to determine the adapter’s usability.

2. Adapter design

The design objective of the adapter was to accommodate individuals with amputations with varying residual limb length to use the isokinetic dynamometer in both stationary (isometric) and dynamic (isokinetic) modes. In addition, the adapter was designed to accommodate the limb with and without a prosthetic attachment. Specifically, the following design requirements were considered:

• Adjustability in three planes to allow for maximal adjustability in the alignment of the axes of rotation of the joint involved in the movement and the dynamometer
• Accommodation for various limb lengths and sizes and for a comfortable interface free of pressure point for comfort.
• The ability to perform a movement in a full range of motion while using the adapter.
• The ability to adjust the adapter in three different planes in relation to the isokinetic dynamometer to facilitate the alignment of the dynamometer attachment to the limb or partial limb of the user without requiring movement of the user
• Construction from a rigid material to allow for data collection in a closed system.
• The adapter should have a limb support configured to conform to the shape of a user’s limb and cushioning material provided on or surrounding the support
• Weight and size of the adapter should be similar to other isokinetic dynamometer adapters.

Each of the considerations above were addressed in the development of the adapter. Consultation was taken with experts in the prosthetic field, a research prosthetics technician, a research prosthetist and a research occupational therapist.

2.1. Materials and dimensions

Various materials were explored when developing the adapter including steel, aluminum, thermoplastic, polyvinyl chloride (PVC), carbon fiber, and vacuum splint technology.

In the material selections, it was assumed that 1¼ inch steel square tubing would be strong enough to support forces that the adapter would encounter. This assumption was based on the fact that structural steel has a greater modulus of elasticity $E$, a greater yield strength, and a greater ultimate strength than aluminum considering that the HUMAC NORM System commercial adapters are made of 1¼ inch aluminum square tubing (Hibbeler, 2014). The technical
specifications for the chosen steel material were as follows: AISI 302, 180 GPa Young’s modulus of elasticity, 860 MPa ultimate tensile strength and 502 MPa yield strength.

It was also assumed that the carbon fiber composite material would be sufficiently strong as it is the same composite material that is often used in the fabrication of prosthetics. In addition, the center of the carbon fiber composite piece was supported by an embedded aluminum plate to add to the strength of the adapter.

The adapter was designed to accommodate users of different anthropometrics. The Military Handbook Anthropometry of U.S. Military Personnel (Metric) (Department of Defence, 1991) was used to guide the selection of the dimensions. It was assumed that a design based on the 95th percentile of the forearm length (31.6 cm) and forearm circumference (33.6 cm) of the US Army Men would fit most trans-radial amputees’ residual limbs (Department of Defence, 1991). The conceptual design is shown in Figure 2.

The adapter was then created in two parts: a steel structure and the carbon fiber receiver creating the interface between the user and the machine. Both parts were custom machined in-house. The steel structure consisted of the adapter frame, and adjuster and the receiver connection (to connect to the isokinetic dynamometer). The height and weight for the 95th percentile male is 185 cm and 98 kg respectively and accommodated by the stainless steel chosen. The detailed design is shown in Figure 3.

The padded limb support includes a curved support configured to conform to the shape of a user’s limb with cushioning material provided on the curved support. For user comfort, the carbon fiber surface was covered with a piece of fabric attached with a hook and loop fastener system (Figure 4). The male side (hook) of the system is glued to the receiver and one side of the selected fabric make the female side (loop) of the system. The fabric pieces were designed in two different shapes to allow for adjustability.

Finally, the adapter is attached to the user with straps equipped with a loop and hook fastener system. The straps were designed to be adjustable for comfort.
2.2. Adjustability

The adapter was designed to accommodate both a residual limb from amputation as well as a prosthesis. Adjustability was critical and the adapter was designed to attach to the isokinetic dynamometer and adjust up and down, in and out of the elbow and in the sagittal plane.

3. User testing

3.1. Methods

3.1.1. Participant

One 64-year-old male who had his right arm amputated below the elbow following a traumatic accident (residual limb length = 22 cm) participated in the testing of the adapter.
The participant was recruited through the Atlantic Limb Deficiency Clinic. This research project was approved by the University Research Ethics Board.

3.2. Instrumentation
The adapter was tested using the Cybex HUMAC®/NORM™ Testing and Rehabilitation System, model 770 (CSMI). All data was recorded with the associated computer software (HUMAC2009v10.000.0037) at a frequency of 100 Hz.

3.3. Testing
The participant was asked to lay down on the isokinetic dynamometer and the adapter was placed over his residual limb and adjusted for comfort (Figure 5). The adapter was then connected to the elbow flexion and extension arm of the dynamometer (Figure 6).

For the isometric testing, the elbow angle was set at 90 degrees as determined by measurement performed by the system software and reconfirmed with a goniometer where the actual elbow angle was found to be between 80 and 84 degrees. The participant was asked to perform a five-second isometric elbow extension practice trial, followed by a 90-second rest period. Then the participant was asked to perform three sets of five-second isometric elbow extensions, followed by 90 seconds of rest.

Once the participant completed the isometric contraction protocol, he was asked to complete the isokinetic testing (elbow flexion and extension). There was a resting period of ten minutes between each protocol to reduce fatigue.

The isokinetic testing occurred through a range of motion between 120 and 135 degrees (measured with a goniometer) depending on the movement tested, elbow flexion or elbow extension. The shoulder was placed in complete adduction with the upper arm along the participant’s trunk. During the isokinetic contraction testing, the participant was provided a practice trial followed by three identical trials with 90 seconds of rest between each trial. While testing the isokinetic flexion, the dynamometer speed was set at 25 degrees per second for concentric elbow flexion and at 90 degrees per second for concentric elbow extension. While testing the isokinetic elbow extension, the dynamometer speed was set at 25 degrees per second for concentric elbow extension and at 90 degrees per second for concentric elbow flexion.

The entire testing protocol (isometric and isokinetic movements) was completed twice with three weeks in between testing days. The strength data were then compared between the two days.

Figure 5. Prosthesis user with adapter fitting.

The user was asked to lay comfortably on the dynamometer and place his residual limb in the adapter.
4. Results and discussion

The shape of the adapter allowed for adequate adjustments to align the axis of rotation of the elbow with the axis of rotation for the dynamometer. Thus, the execution of both isokinetic elbow flexion and extension resulted in a dynamic motion isolated at the elbow.

The participants strength data was compared between two testing sessions separated by three weeks. The results are shown in Table 1.

The strength data suggests that while there were changes in the values of strength attained between days, the participant was able to produce both isometric and isokinetic contractions. The participant was also asked for their feedback regarding the design and the usability of the adapter and the overall fit.

During isokinetic extension, the participant pushed against the adapter with the anterior surface of his forearm and he was able to completely extend and flex his elbow. During isokinetic flexion, the participant pushed against the adapter with the anterior surface of his forearm and thus was able to completely extend his elbow, but his elbow flexion was slightly reduced. The
reduced elbow flexion was caused by the presence of the adapter receiver (one centimeter in thickness) in the cubital region. The reduction in range of motion caused by the interference of the adapter receiver could not be further reduced because of the nature of the task to be executed, the anatomic characteristics of trans-radial amputees, and the importance of a rigid structure for data collection.

The adapter has two different adjustments with respect to its connection to the dynamometer depending on the type of contraction to be produced (for example isokinetic flexion or extension). While the adapter was designed for use in either flexion or extension positions, it was suggested that the adapter be adjusted such that the user must push against the rigid surface of the adapter instead of pulling on the adapter straps. The fabric straps are flexible and do not provide a solid enough interface for the prosthesis user for accurate data collection.

The prosthesis user that was tested did note that the comfort and ease of use could be a concern depending on the length of the residual limb. It was noted that the selected fabric that formed the interface between the adapter and the user caused skin irritation due to its rough surface. The edges of the straps holding the participant’s forearm produced some skin marks that could potentially lead to breaks in the skin. As a remedy to further skin irritation, the residual limb was wrapped in a thin, adherent, and soft material. It was important to have a thin material to avoid restriction in elbow range of motion. Future refinement of the device will consider embedding this material into the adapter for greater user comfort.

One of the challenges of using the adapter is the length of the residual limb. Both prosthesis users who were tested had a fairly long residual limb (19 cm and 20 cm respectively). In order to accommodate a wider range of users, the radius of curvature and the arc length of the receiver should be considered. The adapter fit the only participant that was tested however a larger receiver could have facilitated the adjustment of the adapter to the dynamometer for a perfect fit. A larger receiver would also be needed for users who have larger limbs than the aforementioned participant. For optimal results, there should be participant-specific adjustments of the adapter to the isokinetic dynamometer. The receiver of the present adapter was 30 cm in length. A future improvement to the adapter could be to shorten the receiver to accommodate shorter residual limb length. In addition, a shorter receiver would reduce the weight of the adapter thereby increasing the comfort to the user. In this design wings were placed in the inferior portion of the receiver, however they did not appear to provide any valuable contribution to the use of the adapter and they also caused challenges when adjusting the system and therefore can be removed. One suggestion for a future design is to use a similar shape to the superior portion of the receiver for the inferior portion.

The adapter may be modified in the future, however it is the first of our knowledge to attach directly to an isokinetic dynamometer and allow prosthesis users to operate the machine with

| Isometric Peak Torque (Nm) | Percent Change |
|---------------------------|---------------|
| Day 1 | Day 2 |
| Extension | 34.0 | 26.6 | −21.8 |
| Extension | 44.3 | 50.4 | +13.8 |
| Flexion | 20.0 | 16.1 | −19.5 |
their affected limb. The ability to record both isometric and isokinetic muscle strength data in a controlled environment will help to better estimate muscle function for prosthesis users. In addition, as isokinetic dynamometers can be used for strength training, the ability to connect to these devices will help improve rehabilitation protocols for this clinical population.

While there were some limitations with the current design, the novel aspects of the adapter include:

- The ability to centre the axis of rotation (of the adapter) to an individual with an amputation for accurate force measurements and range of motion estimation.
- The ability to use the isokinetic dynamometer for those with amputations in conjunction with surface electromyography (EMG) for testing controlled, dynamic movements.
- The ability to conduct strength training and testing for individuals with amputations (currently there is not adapter to allow an individual with an amputation to operate this strength training/testing device).
- The adapter is adjustable in terms of accommodating different residual limb shapes and sizes. Ensuring comfort and safety is critical to the patient and data quality.
- The adapter provides a padded interface between the residual limb and adapter components, which is important for reducing compression forces on residual limbs.

5. Conclusions

The adapter designed has a unique shape that allows infinite adjustments to align the axis of rotation of the joint involved in the motion, the elbow in this situation, with the axis of rotation of the dynamometer. The prototype adapter will enable trans-radial amputees to use the HUMAC®/NORM™ Testing and Rehabilitation System and possibly other compatible isokinetic dynamometer for rehabilitation purposes. The prototype adapter, or any improved version, will facilitate improved research that examines trans-radial amputees muscle activity under controlled dynamic conditions.

Nonetheless, further testing is required to assess the validity and the reliability of the prototype adapter used for an elbow range of motion in order to label this adapter a research tool. An additional suggestion would be to test the prototype adapter not only with trans-radial amputees, but also with trans-humeral amputees to determine its effectiveness with shorter residual limb.

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Cover Image

Source: Adapter in Use.

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