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REVERSE ENGINEERING A TRANSHUMERAL PROSTHETIC DESIGN FOR ADDITIVE MANUFACTURING

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Abstract

The customization and time savings additive manufacturing (AM) offers has been applied to construct prosthetics. However, prosthetics produced using AM rarely resemble the original appendage they are intended to replace. This report details the engineering of a transhumeral prosthetic design for AM. A 3D scan of a subject's existing arm and computer-aided design (CAD) were used to create a mirrored prosthetic, which appeared aesthetically like the existing arm. The process and complexities of integrating mechanical components for basic actuation into a patient-custom prosthetic are discussed. A simple demonstration of the process is provided. The same methodology can be applied to more intricate prosthetics. This work aims to inspire subsequent research into well-functioning, custom prosthetics that can be generated relatively quickly through 3D scanning and AM.

Introduction

AM, more commonly known as 3D printing, is a term that broadly encompasses seven categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization. All types of AM create parts by adding material layer by layer, but traditional, subtractive manufacturing techniques usually involve removing material from an existing block of material to obtain the final part [1, 2]. While both processes have their own advantages and disadvantages, AM is becoming increasingly popular and widely used because it allows for parts to be rendered quickly and is becoming more affordable for industrial applications. The model detailed in this report was produced using fused deposition modeling of a polymer filament.

Since its debut in the late 1980s, AM technology has advanced dramatically. With recent technological advancements making AM cheaper and more accessible, there has been a remarkable increase in its applications to the medical field, especially regarding physical medicine and rehabilitation [3]. A couple decades ago, AM was employed and researched, nearly exclusively, by corporations and scientists. Currently, multiple companies have small, desktop 3D printers that are available to purchase for private use at a relatively low cost. Various free websites (Thingiverse, Grabcad, Sketchfab, etc.) allow users to upload and download stereolithography (STL) files for virtually effortless printing on desktop printers. It is important to note how accessible 3D printing has become. This report details the design and construction of a custom, actuated prosthetic designed for a transhumeral amputee produced via laser scanning and AM.

Prosthetics allow amputee patients a fraction of their original limb's functionality. As prosthetic technology develops over time, this fraction increases. Mimicking the human body's functions can be challenging, especially when incorporating mechanical components into prosthetics. Due to this challenge, many modern prosthetics look bionic and strikingly industrialized (Figure 1). Although they can return some functionality to patients that would otherwise have to learn to live without an appendage, such prosthetics lack the ability to appear aesthetically similar to the original limbs.

In recent years, research has been focused on integrating sensory feedback controls into prosthetics so a sense of touch can be returned to prosthetic users (i.e., they can feel temperature, surface textures, and pressure). Research efforts by Massachusetts Institute of Technology (MIT) have yielded prosthetics, which use rerouted electrical signals that previously connected the limb and the spinal cord to the patient's chest muscles. An electrode placed on the patient's chest can then process contractions in the muscles and relay the signal to the prosthetic. This allows the wearer to distinguish the difference between hot and cold items and feel pressure applied to the prosthetic [4,5]. However, more exploration is needed of how to better integrate the necessary electrodes and equipment into the body of the amputee as well as the prosthetic.

Figure 1. Examples of current transhumeral prosthetics (from left to right: Northeast Advanced Surgery and Prosthetics, Defense Advanced Research Projects Agency's)

Although AM has allowed multiple companies to manufacture cheaper, more complex parts while saving time, it is not always the most logical solution. For example, if a part is being produced cost-effectively and successfully through traditional means (e.g., injection molding, casting, etc.), it is not logical from a business perspective to try to duplicate an economical process via AM unless it offers extreme novelty or significantly improves the part in question. For such processes, AM would be time-consuming, expensive, and could place constraints on part size. However, AM does offer certain manufacturing advantages. It is especially useful when the design calls for customization and lightweight-components. For instance, research efforts and clinical applications of AM have become more widely used for custom, patient specific internal implants, resection guides, and external braces [6]. When designing for AM, it is possible to combine components that may not have been combined in traditional manufacturing, and topology optimization enables the fabrication of complex, lightweight structures. It is even possible to integrate actuation into additive manufacturing [7]. Part count consolidation, ultimately, increases the reliability of the overall system and can make assembly much more efficient. Additionally, one human body is vastly different from another, but traditional prosthetics have somewhat of a “one size fits all” design. However, amputee patients want a prosthetic specific to their amputation, size, and daily functions. For example, it is expected that a growing child will need multiple prosthetics over a relatively short period. This issue is easily solved with AM as AM would allow for a new prosthetic to be printed periodically when the child would, inevitably, outgrow the previous version. Previous companies have been established to making affordable, custom prosthetics via AM. For example, e-NABLE is a company that specializes in hand prosthetics [8]. e-NABLE addressed the lack of customizability in prosthetics by creating an open-source community that offers STL files to print prosthetics. They take it a step further by connecting those who want to print a hand prosthetic but may not have access to a 3D printer with people who have printers. Similarly, Easton LaChapell founded his company, Unlimited Tomorrow, with the intent to make AM prosthetic technology more available to all. Applying laser scanning and AM to prosthetic design allows for better fitting and functioning prosthetics that are made quickly and aim to aesthetically match existing appendages. This makes custom prosthetics produced via AM competitive and appealing not only from a business standpoint, but also from a patient’s perspective of wanting to have prosthetics that resemble their original appendage.

Methods

A first-generation Sense 3D scanner produced by 3D Systems was used to obtain a raw scan of the subject’s left arm (Figure 2, left). From the raw point cloud, a STL file was generated. Geomagic, a SolidWorks add-in, was used to generate an automatic surface from the exterior portion of the arm. This surface was used to create a solid model of the arm. Manual modifications were made to the solid model to address areas that were affected by noise during the scan. With simple CAD manipulations, the solid left arm model was mirrored to form a right arm model. Next, most of the model was shelled to a thickness of approximately 0.15 inches (Figure 2, right). The hand portion was not shelled because of its geometric complexity.

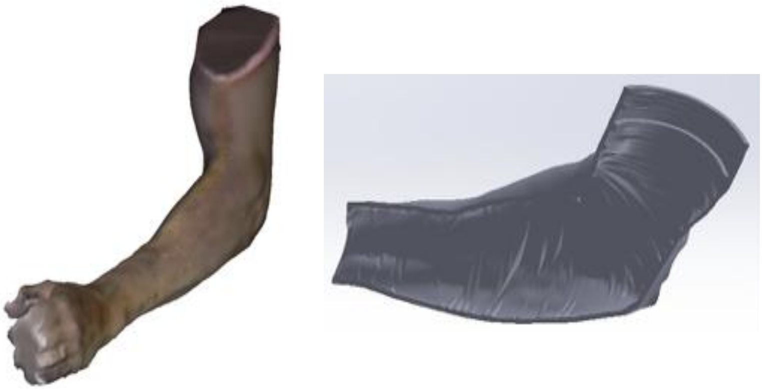

Figure 2. Raw scan from 3D Sense Scanner (left) and cross-sectional rendering of shelled, mirrored arm (right)

Initially, it was thought that the model would be partitioned into three different sections: upper elbow, elbow, and forearm/hand. It was intended that both the upper and lower portions be printed from acrylonitrile butadiene styrene (ABS) while the elbow portion be printed from Ninjaflex, a material defined as “an innovative thermoplastic elastomer 3D printer filament” [9]. Ninjaflex is a thermoplastic elastomer (TPE). It was thought that this partitioning would be flexible enough to allow for the movement induced by the actuator. However, it quickly became apparent that the Ninjaflex filament was going to be difficult to print on the available machines. Therefore, two primary sections were fabricated from ABS and connected by a single hinge joint. Ultimately, a better material should be used for end-use applications, but ABS was sufficient to demonstrate the efficacy of the proposed method.

The hinge joint approach was simpler than the original design, as it more accurately mimicked the function of a natural elbow, and it only consisted of four portions, which were all printed from ABS. After the lower and upper portions were defined in the model, the interacting surfaces were both reduced by 0.1 inches to allow for clearance needed for proper motion of the model. The new model consisted of four basic parts: the lower portion, the upper portion, the actuator, and the interior mounting boss for the attachment of the actuator (Figure 3). The lower portion and upper portion acted as the distal and proximal sections of a hinge joint, respectively. This gave the model the possibility of uniaxial motion.

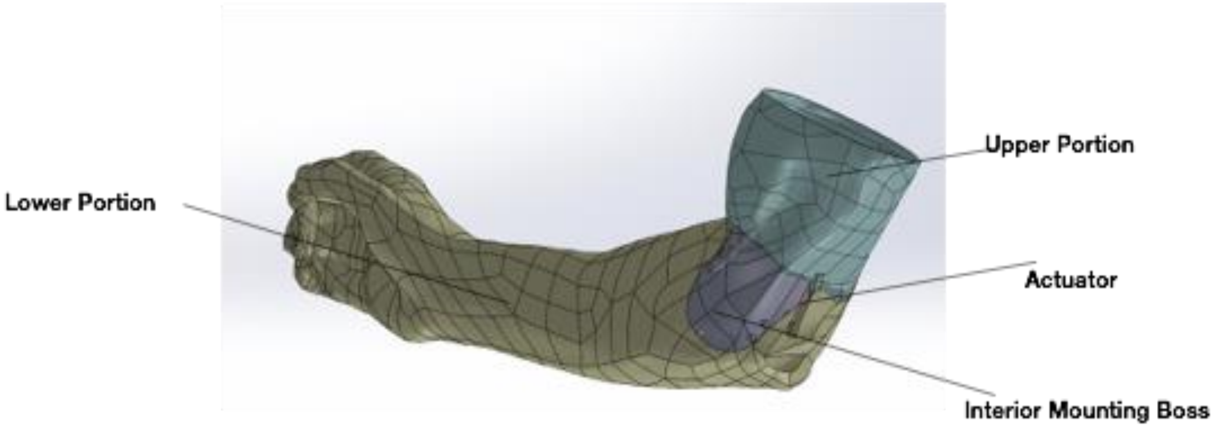

Figure 3. Revised model with annotations

To obtain the desired actuation of the prosthetic, a rotary actuator was introduced to the system. Although an air powered actuator does not replicate the functionality of an elbow, it was chosen for simplicity. The compact rotary air actuator used had an outer diameter of 1.97 inches and provides 90 degrees of rotation (Figure 4). Compressed air was used as the air supply to the actuator. Additionally, quarter-inch tubing, two pneumatic two-way valves with speed control, ninety-degree fittings, and an air source connector were added to the model.

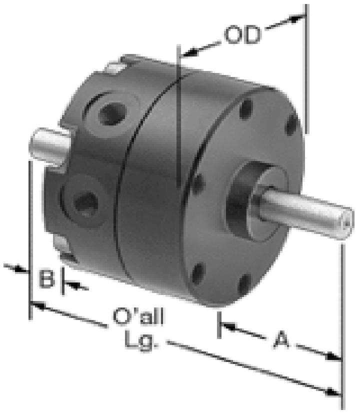

Figure 4. 6508K14 Compact Rotary Air Cylinder (McMaster Carr)

The lower portion, or the forearm, (Figure 5) primarily consists of the hand, forearm, and elbow. To allow for proper actuation without intersecting features, four slits—two in the anterior and two in the posterior area—were made in the lower portion (Figure 6) for both brackets housed in the upper portion. Additionally, a boss extrusion that holds the shaft of the actuator stationary was added to the lower portion to provide correct initial placement of the actuator and to increase stability (Figure 7). A hole was drilled post-print on the flat portion of this boss extrusion. A corresponding hole of the same dimensions was drilled in the shaft of the actuator. A pin was used to connect the two. Holes intended for #6 screws were drilled and tapped post-print on the flange section of the lower portion. This allowed the interior mounting boss to be screwed into the lower portion to conceal the inner workings of the model after the actuator was installed.

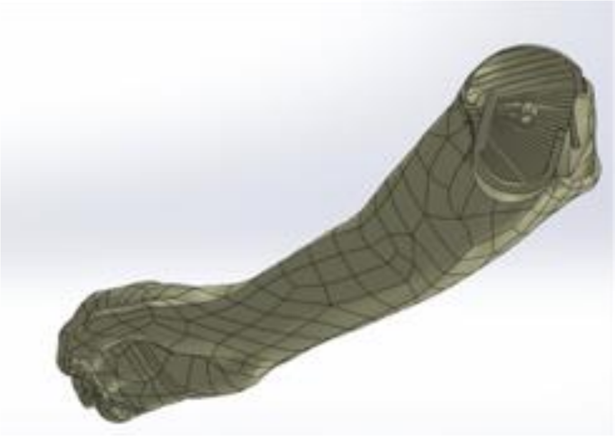

Figure 5. Lower portion

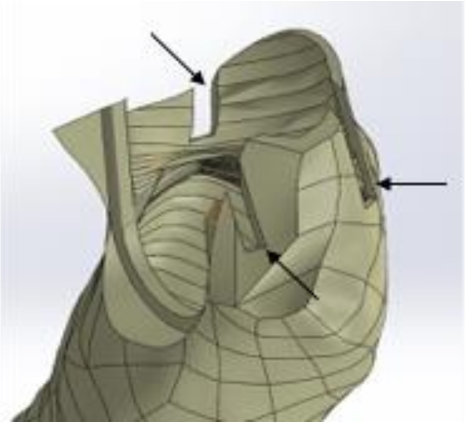

Figure 6. Slits for interaction with the upper portion’s bracket

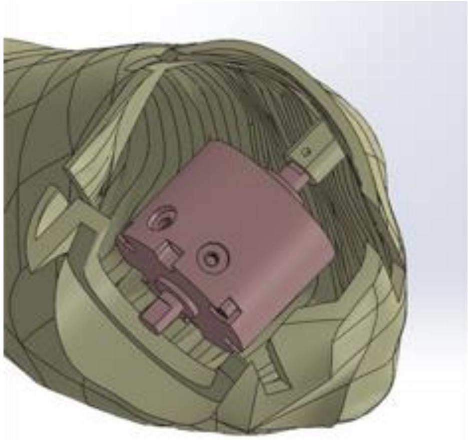

Figure 7. Actuator placement within the lower portion

To properly integrate the actuator into the design, two brackets were created and added into the upper portion (Figure 8). Designing via AM allowed the brackets to be printed to the upper portion thus reducing complexity, part count, and weight. The brackets allowed the actuator to be easily placed into the correct location during the assembly of the prosthetic. The flanges added to the bracket functioned as support for the stress the model underwent from the motion caused by the actuator (Figure 9). Part of the anterior upper portion was removed to prevent interface during actuation.

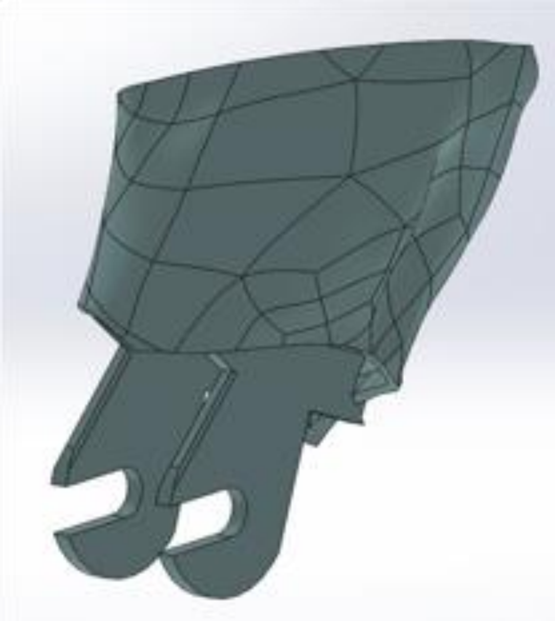

Figure 8. Upper portion

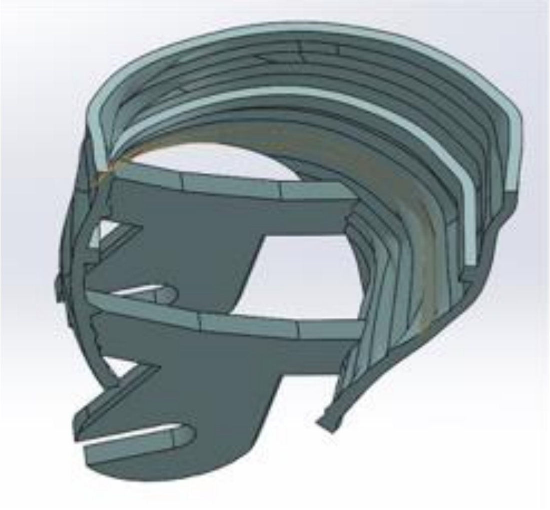

Figure 9. Section view of the upper portion showing bracket flanges

To make installation and interaction with the actuator portion of the model more accessible, a section of the lower portion was separated and used to create a detachable piece (Figure 10). Screw holes designed for a #6 screw were created to attach the interior mounting boss to the lower portion of the prosthetic. A boss extrusion, like the one located in the lower portion, was added to mate with the other shaft of the actuator. This extrusion provided additional support to the actuator, especially to assist with the device's motion.

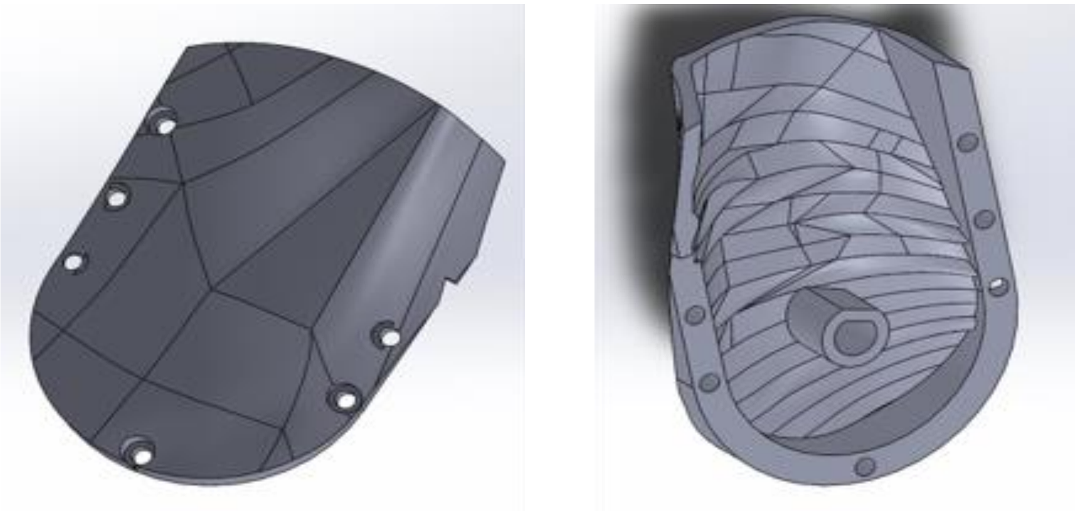

Figure 10. Exterior view of internal mounting boss (left) and internal view of interior mounting boss (right)

The prosthetic was fabricated using ABS on a Stratasys Fortus 400mc Production 3D Printer. To reduce the amount of support material needed, the lower portion was printed in two separate segments: the hand and the forearm. Therefore, the model was printed in four separate parts: the upper portion, the interior mounting boss attachment, the hand, and the forearm. The print used 45.3 cubic inches of ABS and 19.1 cubic inches of support material to build the prosthetic. After the approximately 47-hour print, the parts were placed in a solvent bath of Stratasys' alkaline cleaning solution for five hours to dissolve the support material. All the printed pieces of the model turned out to be remarkably similar to the SolidWorks model. Filing of the anterior and posterior slits on the lower portion and the lateral interface between the lower and upper portions was needed to remove interference of the pieces during actuation. The pieces were assembled accordingly. Figure 11 shows the placement of the actuator inside the model.

Figure 11. Model with interior mounting boss attachment removed to show actuator placement

Perhaps one of the biggest advantages of AM is the ability to make lightweight components. Considering the upper arm, forearm, and hand comprise approximately 5.7% of a person's bodyweight [10, 11] and the adult male used as the subject in this study has a bodyweight of 235lb, the approximate weight of the subject's arm is 13.4 lb. The prosthetic manufactured in this study, including the actuator, had a total weight of 2.2 pounds (Table 1), yielding an 83.5% reduction in weight. A similar, lightweight prosthetic structure could allow more weight to be allocated to actuation, sensors, energy storage, etc. in future prosthetic designs.

Table 1. Prosthetic Component Weights

Component	Weight (lb)
Actuator	0.6
*Hand	0.45
*Lower Portion	0.66
*Upper Portion	0.42
*Interior Mounting Boss	0.06
Total	2.19

*indicates the component was fabricated via AM

Overall, this project objective was met as a custom prosthetic, capable of actuation, was derived from laser-scanning and fabricated using AM. As seen from the resolution of the print, the laser scan provided a lifelike detail to the prosthetic not previously achieved. The accuracy of the prints can be seen in Figures 12 and 13.

Figure 12. Side view of the subject's arm and the mirrored prosthetic

Figure 13. Top view of the subject's arm and the mirrored prosthetic

Conclusions

There were some sections of the model, especially in the hand area, that did not aesthetically match the existing arm. This can be attributed to noise from the original 3D scan of the arm as the STL obtained was a function of scan resolution. The 3D Sense scanner used in this project was relatively cheap (approximately $300). It is likely that a better-quality laser could produce a sharpened raw scan with less noise.

The prosthetic created was relatively simple. It does not have individual, functioning fingers but rather a "mitten" hand. This model also lacks extension, flexion, and rotation of the wrist and rotation of the elbow. As it was not intended for actual use, it does not have a feedback system nor could it be fitted to an amputee patient. Additional research needs to be completed to integrate the state-of-the-art technology of sensory feedback. Additionally, surface modification of the printed prosthetic could be introduced to fix deformities in the SolidWorks model. The use of a linear electrical actuator or solenoid instead of a rotary air would be a more realistic option for a prosthetic model.

The research and techniques used in this paper can be applied to numerous other areas to reverse engineer a part. Additionally, this work could be integrated with state-of-the art prosthetics such as ones that allow the user to experience sensory feedback. Prosthetics produced this way could be enhanced and advanced by using higher quality materials. For example, the prosthetic could be printed from polyetherimide (Ultem), which has nearly triple the tensile strength of ABS. Ultem offers excellent chemical resistance and dielectric effectiveness and is available in Food and Drug Administration (FDA) compliant grades. Similarly, the use of superior actuators, capable of offering increased actuation velocity while handling greater torques, could be used to create a more advanced prosthetic. Lastly, fit and power source options need to be explored to increase functionality and usability.

Acknowledgements

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References

1. ISO / ASTM52900-15, Standard Terminology for Additive Manufacturing – General Principles – Terminology, ASTM International, West Conshohocken, PA, 2015, www.astm.org
2. Lunsford, Grindle, Salatin, and Dicianno. "Innovations With 3-Dimensional Printing inPhysical Medicine and Rehabilitation: A Review of the Literature." PM&R 8.12 (2016): U;. =[
3. Wohlers, Terry, and Tim Gornet. "History of Additive Manufacturing." *Wohlers Report* 24 (2014): 2014.
4. Rosenwald, Michael. "A Lifelike Prosthetic Arm." *Technology Review* 112.3 (2009): 76-77. Print.
5. Talbot, David. "An Artificial Hand with Real Feeling: A New Nerve Interface Gives a Sense of Touch to a Prosthetic Limb." *MIT Technology Review* 117.2 (2014): 48. Web.
6. Fitzpatrick, Mohammed, MI, Collins, PK & Gibson, I 2017, 'Design of a Patient Specific, 3D printed Arm Cast', KnE Engineering, vol. 2, no. 2, pp. 135-42.
7. Love, Lonnie J et al. “Freeform Fluidics.” Dynamic Systems, Measurement and Controls 135.6 (2013): n. pag. Print.
8. Brown, Alan S. "Q&A: Jon Schull.(TECH BUZZ: ONE-ON-ONE)(founder of a Volunteer Organization Enable Community Foundation (e-NABLE))." 137.8 (2015): 18. Web.
9. "NinjaFlex(R) 3D Printer Filament Introduces Fresh Colors and New Website." Internet Wire 08 Sept. 2014: Internet Wire, Sept 8, 2014. Web.
10. De Leva, Paolo. "Adjustments to Zatsiorsky-Seluyanov's Segment Inertia Parameters." *Journal of Biomechanics* 29.9 (1996): 1223-230. Web.
11. Plagenhoef, S., Evans, F.G. and Abdelnour, T. “Anatomical data for analyzing human motion.” *Research Quarterly for Exercise and Sport* 54 (1983), 169-178.