Developing Wearable Assistive Materials for Orthopaedic Applications - 3 Month Report

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Abstract

The development of WAM, a smart material capable of changing between rigid and flexible configurations to provide a thin, light exoskeleton for a range of mobility disorders, is an ambitious interdisciplinary effort, and one to which modelling and simulation have not currently been employed. The exact nature and underlying structure of the material have yet to be fully elucidated, though the need for such a product and the potential actuators worth investigating have been made clear in a previous report [1]. Several new conceptual contributions relating to the structure and mechanisms of WAM are presented here. The aim of this report is to consolidate what I have learned, worked on and read about since joining the WAM research group, to demonstrate how modelling and simulation could prove important in the project, and to state what I intend to produce, in terms of theory, software and physical prototypes, in the coming months.

I. Introduction

The following questions have emerged as fundamental to this project;

1. Is it possible to elicit support of muscular movement through a layer worn on the surface of the skin?
2. How would such a layer produce the necessary force, in terms of stiffness and movement, whilst remaining sufficiently light and thin?

In the natural world joint movement is accomplished almost universally through the contraction of muscles attached to pairs of bones. Conventional man-made exoskeletons employ similar techniques using hydraulics, or alternatively direct rotation at the joint is achieved through motors. Both of these actuation systems are heavy, often deemed unsightly and are energy intensive, requiring high capacity batteries and frequent recharging. Despite being successful in replacing or enhancing muscle function, such devices are not yet commonplace in society at large for reasons outlined above and in [1].

In theory, a shell capable of freely changing shape could morph between two volumetric profiles of a limb under movement, causing the body within it to move correspondingly. However, the distribution of forces required and the exact nature of the shape changes over the surface is currently unknown and something I intend to investigate.

Whether the forces produced across a thin layer of smart material are sufficient for orthopaedic applications depends on both the actuators used, and the way they are included within the material as a whole. As an alternative to traditional robotics, we are considering solid state actuators, a relatively unexplored field. For our purposes the most promising substance in this class is *Vanadium Pentoxide* (V_2O_5), the fibres of which intercalate ions under the application of small voltages resulting in a net expansion. A bimaterial strip consisting of two V_2O_5 fibre sheets is observed to bend as one side expands (intercalates) more than the other, with the direction and severity of bending being controllable through adjusting the voltage across each side. Refinements to the intercalation speeds, hysteresis and ionic media for V_2O_5 are being pursued by the WAM team, though in my work I shall consider general solid state actuators, in the event that alternatives are used further down the line.

A reasonable goal for my contribution to the project at this stage would be to establish a generalised structure into which V_2O_5 or similar actuators could be incorporated, whereby a network of multiple small-scale expansions, contractions or folds combine to enact a more complex change in shape and stiffness of the "material" as a whole. It has been suggested that chain-mail would be a good class of structure to investigate due to it being flexible yet mechanical, and possible to manufacture with 3D printing. The chain-mail/actuator composite would sit within a layer of porous gel, which would serve as an ionic medium for the actuators as well as providing smoothing, and the entire system would be encased in a thin layer of rubber to prevent the gel from tearing and evaporating. As the boundaries between material and machine become blurred, we intend to produce frameworks through which a patch of such a material could either be constructed to generally change shape, with the exact behaviour programmed later and coordinated through a micro-controller, or a material that is designed and then fabricated to produce one specific behaviour upon activation.

II. Types of WAM

Clearly the applications of a smart, shape changing material are myriad. Interest from the aviation sector has come from Airbus, as the material could be used to produce lighter and more comfortable seats or eventually shape changing wings. Morphing aircraft has in the last decade been a hot topic across the industry, with NASA [2], Lockheed Martin [3] and DARPA [4] among some of the organisations to have commissioned studies into the advantages such technology would bring to many aspects of flight; aerodynamics and fuel economy being chief among them. Similarly, large scale morphing structures have been considered for use in the wind turbine industry [5]. The techniques currently used for modelling, parameterising and optimising hypothetical wing morphing could be employed in the development of WAM.

Interest has also been shown from the civil engineering industry, where shape changing buildings could neutralise the impact of wind [6] and seismic [7] activity.

Within the medical sphere, other applications considered have included shape changing stents for vasculature prostheses, and a device that could be activated inside the respiratory system to aleviate snoring.

The nature of WAM seems to require research to be divided between two different classes of smart material; static and dynamic, and theory arising from this distinction could have wider implications in smart materials research as a whole. Static devices, for example a fracture cast that could be made flexible for periods to aid rehabilitation, would at first seem to be substantially simpler due to the lesser degree of electronic control required. The device would be either in a flexible or a pre-defined rigid state, and it is conceivable that a chain-mail lattice could be constructed algorithmically to have a specific profile under stiffening.

However, this would not be very energy efficient, requiring constant voltage to be maintained across the actuators in order for the material to perform its function of remaining rigid. A system utilising pairs of actuators to switch the microstructure between two mechanical states would use energy only when changing from soft to rigid, and thus would need to be charged far less frequently.

Unsurprisingly, examples of such structures are scarce, with most of the literature on locking mechanisms being of the more conventional type found in doors and industrial tools. One relevant example is a patent filed in 1998 for an expandable locking stent [8] arising from a mesh of interwoven helical fibres. Under compression, the structure grows in the radial dimension enough to compensate for damaged vasculature. The ends can then be locked into place either through an axial bar or attachment to the surrounding tissue.

For the other, dynamic WAM problem, locking structures would also be beneficial or perhaps even essential, whereby the chain mail is locked immediately upon engaging the actuators, and then varying degrees of additional actuation are responsible for shape change in the rigid state.

For initial conceptualisation and prototyping, static structures without locking mechanisms, i.e. ones where voltage must be maintained, would seem a sensible starting point. How I intend to do this will be covered in Section VI.

III. Musculoskeletal Modelling

This class of modelling and simulation is inherently critical for the development of WAM across all stages. During the initial exploration of actuators and composite design, the forces and morphological changes across the joints we hope to rehabilitate must be used as a benchmark for strength and flexibility, and musculoskeletal (MS) modelling packages are excellent for this. They serve as both a comprehensive repository of our empirical knowledge on MS physiology, and a well supported engine for conducting *in silico* MS research.

The two most highly regarded software packages in this field are AnyBody and OpenSIM, and we have been evaluating which one would be best suited to our requirements. Both suites permit the construction of MS systems and allow for the full plausible range of motions to be described. Motion can be captured from living subjects, the models fitted accordingly so that forces may be computed and abnormalities at the muscular level may be inferred. Additionally both packages are used to explore the modification of MS components as a guide for surgery, prosthetics and implants. Critically, both permit the importing of objects from external CAD packages for the study of environmental interaction, ergonomics and optimal product design, and both have been used to model traditional robotic exoskeletons and their effects on the host body. Nothing quite like WAM, a "continuously" deformable exoskeleton, has been modelled in either suite, but the nature of our research was posed to OpenSIM expert Jeff Rankin and he believed it would be possible in this package.

AnyBody features *AnyScript*, an object-oriented programming language similar to C++ and Javascript, and also a direct interface with popular CAD system SolidWorks which will be investigated in the next section. OpenSim has a pipeline to Matlab, a language with which I am very familiar, for importing motion-capture data and more advanced analyses of OpenSim output. The software has a well supported Application Programming Interface (API) which is also accessible through Matlab.

To address our first fundamental question of whether joint motion could be elicited through a layer worn on the surface of the skin, a model of a WAM type device could be placed onto a MS model, and then motion simulations conducted. The primary obstacle here is the addition of flesh to the MS armature, since skin contact is essential to WAM's functioning as we understand it now, and neither software suite supports such modelling natively. No alternative suites have been found that offer both force analysis and flesh/contact modelling. It is here that I believe OpenSIM will prove superior due to its open source architecture and its extensive support community from the academic - as opposed to more secretive industrial - sphere. This issue could be approached through capturing a 3D model of a real life subject's joint, fitting the MS model in OpenSIM and then applying the moving flesh over the top as an object. During simulation, motion would be first provided by the WAM, with the 3D flesh model underneath acting as a constraint on its geometry, and the forces then transferred to the MS model, which at this point has had its own muscle function impaired. The large number of additional boundary conditions required in such a problem would quite likely be beyond what is achievable with AnyBody's scripting environment, and may require more fundamental modifications of the source code.

For this reason, combined with the fact multiple licenses will be required, something that could be prohibitively expensive with AnyBody, I would say that OpenSIM is the software that should be used from here on.

As a somewhat superficial side note, OpenSIM shares its name with an open-source platform for hosting virtual worlds, which can make searching for resources often confusing as there is significant overlapping terminology between the two.

IV. CAD Packages

Computer Aided Design (CAD) software is used extensively across the design, engineering and manufacturing industries to facilitate accurate blueprinting, modelling, simulation and analysis of objects prior to physical prototyping. Development of a product as complex as WAM requires modelling, simulation and optimisation across a number of layers. The hierarchy for a complete WAM model is structured as follows:

$$\begin{array}{c}\text{Electronics}\\ \downarrow\\ \text{Actuators}\\ \downarrow\\ \text{Chain-mail / mechanical lattice}\\ \downarrow\\ \text{Multilayer composite (gels, rubber etc.)}\\ \downarrow\\ \text{Human joint movement / locking}\end{array}$$

For some applications certain layers can be neglected or simplified (eg. to investigate WAM's effect on a joint, modelling the actuators and chain-mail may not be necessary as long as the overall shape change occurs as expected).

Finding CAD packages capable of modelling the first three layers and then providing compatibility with OpenSIM for the fourth is an important part of the project at this stage, so several of the most prominent suites are reviewed below.

Sketchup is a free, open-source CAD package from Google, and is intended to be very easy to use. It has good compatibility with other CAD suites. However, whilst components can be fixed at points and manually rotated, the software does not provide animation, analysis functionality, or parameterised dynamic components, rendering it unsuitable for our needs.

OpenSCAD is an alternative open-source option, and has the distinction of not having a graphical user interface in the sense of most modern CAD programmes - all design features must be implemented purely with code, from which renders can be produced for verification. This allows for the programmer to have in my opinion a more direct connection with their design, whilst the highly parametric nature combined with the software's open-source architecture could prove useful when exploring WAM under varying degrees of actuation.

SolidWorks is a high-end professional suite with a vast number of analysis tools built in. It contains a considerable materials library, which proves invaluable when dealing with mass and other physical properties, and excels in the design of complex assemblies consisting of numerous interacting parts. Finite Element Methods are available for studies of stress, strain, and temperature among other forces, and electronic circuitry is well integrated. It is also at its core completely parametric, though this can be obscured by the rather labyrinthian user interface. Initially seeming to be a very promising option, we found that modelling the actuators in SolidWorks proved tricky. As the name implies, the package is not designed to work with parts that bend of their own accord, most likely because the field of solid-state actuators is at this point still relatively obscure. The bending of a bi-metallic strip could be simulated through finite element methods, but such techniques are computationally intensive and not good for the lowest layer of our model hierarchy.

When recently asked to produce a CGI video of a WAM-type structure in action for Airbus (Fig. 1), after exploring the above options I settled on using Blender, an animation suite. Since unlike SolidWorks the programme is not constrained by the laws of physics (though they are optional), images and videos can be produced of just about anything, and it was possible to animate bending strips of actuator, and a larger dynamic structure built from such strips connected by static nodes. The structure is shown morphing through a range of shapes with and without a flexible gel case, to illustrate the smoothing effect this has. Whilst Blender is excellent for producing demonstrative content, it lacks the analytical tools and programming elements required for the development of WAM.

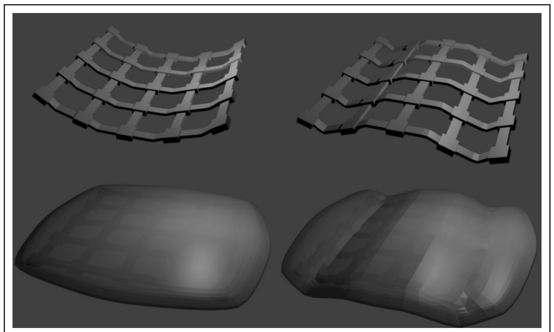

Figure 1: Stills from the simulated WAM demonstration created for Airbus. Top: the mesh of nodes joined with bending strips of actuator. Bottom: the mesh encased in a layer of gel.

Although dynamic, the structure produced in Blender is not flexible in the sense that chain-mail is, but rather rigid, assuming that the actuators themselves are bent only by actuation. Such a smart material if realised would no doubt have many uses but is unsuitable for WAM since flexibility is essential in a wearable device. To achieve controllable flexibility, chain-mail type frameworks seem the most plausible approach.

All of the above mentioned CAD packages have their strengths, but we have yet to find an all-encompassing system for modelling WAM, where signals from a micro-controller are mapped through the hierarchy to produce large scale changes in the material or even the patient. At this stage it would be sufficient for software that accurately models actuator response and its effect on the individual chain-mail linkage it is embedded within, and then how a system of such linkages would behave under a spatially varying actuation distribution. This would allow for us to explore many different chain-mail designs and optimise them for a desired output.

We developed CMmesh.m, a very simple Matlab function that takes an individual chain-mail linkage in the form of a .xml file, and produces a mesh (also .xml) by duplicating the linkage over a given range. However, whilst excellent at linear algebra Matlab is not built for graphical problems and was slow even for this simple algorithm. A research group at UCL led by Gennato Sennatore and Chris Wise have developed "Push Me Pull Me 3D" (PMPM), a software package for designing node-and-rod structures and testing their strength under various forces. Since they too have an interest in controllable dynamic structures for civil engineering applications, they have implemented a function in the software whereby the angle between certain rods can be adjusted using an "actuation" slider, resulting in shape changes overall. A similar programme allowing construction, actuation and analysis of actuated shape changing chain-mail, would be ideal for our purposes. Their software was developed in Java, and this would seem to be a good platform for software involving calculations and real time rendering. However due to the computationally intensive nature of our work it may be preferable to work in C++, using OpenGL for rendering, and these are the languages I have been learning.

V. Mechanisms and modelling

Perhaps the most fundamental theory behind WAM is that describing how one shape morphs to another, a topic that has been massively implemented in the animation and special effects industries over the last 30 years, though not so much with physical objects. In Figure 1 we saw a structure morphing through the bending of its connecting rods. However such morphing is uniaxial - the surface could be morphed into a cylinder but not a sphere. True 3D shape morphing requires expansion and contraction at various points across the surface as Figure 2 illustrates. This is also observed when bending a drinking straw, where the corrugations expand to provide additional surface area, and this is how I see shape morphing working in WAM.

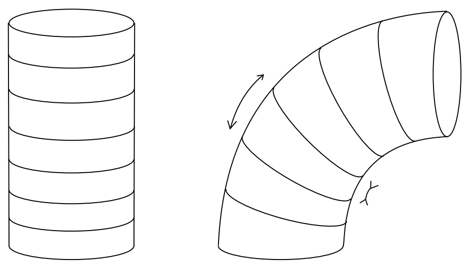

Figure 2: The bending of a cylinder requires contraction along the anterior side and expansion along the posterior.

Through actuator-driven corrugation the cain-mail linkages could change size, and this alone may be enough to facilitate movement of the enclosed body depending on how WAM is bound to the patient. It could also be used to affect the flexibility. Unsurprisingly, little research exists on the modelling of chain-mail flexibility, and this is where our own software developed with C++ and OpenGL will prove useful.

An important concept to be introduced here is the *maximum curvature* (Fig. 3). Assuming uniform linkage shape across the mesh, the chain-mail may be flexed up to the point where linkages collide and the structure becomes rigid. In differential geometry the curvature at a point on a surface is defined as

$$\kappa = \frac{1}{R}$$

where R is the radius of the *osculating sphere*, the sphere sitting tangential to the surface at that point and approximating the surface shape as accurately as possible. Hence for a given chain-mail design, the maximum curvature is defined, and our software will attempt to determine this as a function of how the linkage geometry is parameterised.

Subsequently for a given 3D shape that is topologically equivalent to the chain-mail, a distribution of linkage expansion and contraction could be found to achieve morphing to the desired profile.

Figure 3: A sample of 3D printed chain-mail being flexed to its maximum curvature.

Some relevant research fields and papers are now outlined:

In *Gibson, 1997* [9] a "3D chain-mail algorithm" was devised for computing and rendering disturbances to 3D volumes, for applications such as heart surgery simulation. Such computations were at the time too computationally intensive to be conducted through finite element methods on even the most powerful machines, and are still a challenge now, but Gibson presented a novel method where the mass was modelled, in effect, as a cluster of 3D chain-mail. As such, forces acting at a point on the cluster would move linkages around, and such movement would propagate through the mass with decreasing effectiveness as it was absorbed by the slack in each successive link. Through adjustment to the size of the linkages, the simulated material's elastic properties could be controlled. The algorithm was implemented in C and visualised using OpenGL. It was simple and ran in realtime, and clearly it has considerable overlap with what we will be doing.

More recently, the term "4D printing" has been applied to 3D designs that are able to take on different forms upon leaving the printer. *Hyperform* is a concept to come out of MIT in a collaboration between Skylar Tibbits, the pioneer of 3D printables that change shape upon contact with water, and Marcelo Coelho, who's PhD explored Nitinol based smart fabrics. In Hyperform large chain-mail type structures (the famous examples being a chandelier and a 15m chain) are run through an algorithm to determine the optimal way they may be folded so as to be manufacturable within the volume of a 3D printer. After printing, the mass is unfolded to reveal the finished work. The authors intend to release the software to the public later this year.

Similarly, *"Kinematics"* is a Java programme by Boston based design house Nervous System, where structures made from adjoined hinged pieces are algorithmically folded to aid printing. The software has been used to produce an array of jewellery and clothing within a single print.

In mathematical combinatorics the research field of *structural rigidity* [10] concerns rod-and-node structures like those produced in Push Me Pull Me and the ways such structures can deform given that the rods are free to rotate spherically around their nodes, but may not change in length. Though I have not found a direct use for this theory yet, I anticipate it will become important when we are considering means of making the material remain in a rigid state without requiring any power.

VI. Prototyping

As our actuated chain-mail modelling suite is developed, physical copies of the various chain-mail designs and sizes will need to be printed to inspire and validate the models. In tandem with the software it is our intention to produce a prototype patch of shape changing chain-mail by March, to test hypotheses on folding linkages and decide how best to proceed in the future. The initial patch will be small (5x5 linkages) and will feature Nitinol actuators since the V_2O_5 fibres are still in development by our chemists.

Nitinol is a Nickel-Titanium alloy that can be trained to remember a specific shape; a shape memory alloy. Following plastic deformation the metal will return to its memorised shape with considerable force when heated to its transition temperature. By running current through a Nitinol wire, the temperature is raised due to Joule heating, and so the alloy may be used as an electronically controlled actuator.

By running a Nitinol wire up and then back down a double wire insulator we produced a "Nitinol finger" (Fig. 4) which was trained to bend upon connection to a battery. This has the advantage of only requiring connection to a power source at one end of the actuator, which would simplify wiring in the prototype. However, the rubber insulator used here was not elastic enough to restore the actuator to is initial position upon disconnection from the battery, so we may have to use one side of the tubing for a dedicated restorative Nitinol wire.

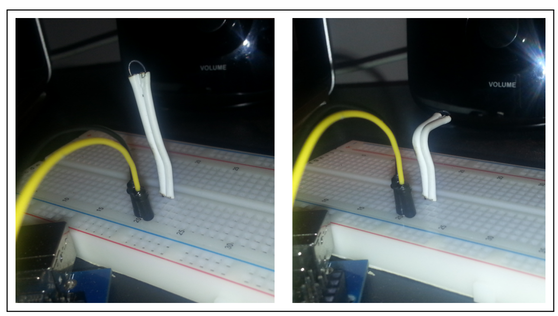

Figure 4: A "Nitinol finger" in its initial (left) and electrified (right) state.

For a very first prototype we have obtained Nitinol springs with tensile strength. We propose printing a set of large chain-mail linkages with adjustable length (Fig. 5). By nesting a contractive Nitinol spring within a standard one and insulating them from each other, the linkage length can be adjusted electronically.

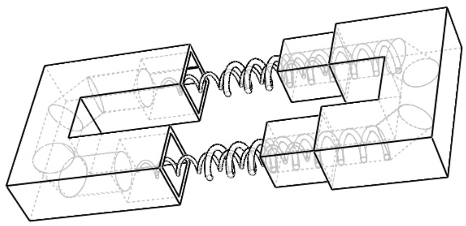

Figure 5: The expanding chain-mail linkage we intend to create. Note the nested pairs of springs - one to drive expansion and the other (controllable Nitinol) contraction.

The springs will each be attached to the interiors of both halves of the linkage. The set of linkages will be assembled into a chain-mail lattice as shown in Figure 6, with each linkage being wired into an Arduino Mega. This prototyping micro-controller board has 54 output pins, more than sufficient for a 5x5 lattice with coupled actuated springs in each linkage. However, the Arduino is unable to provide the currents drawn in activating our Nitinol, so a relay driver board would be required to provide the additional power. For larger lattices, multiplexing techniques may be used to accommodate the additional outputs.

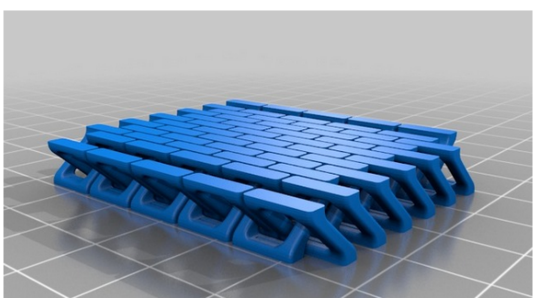

Figure 6: The chain-mail grid we intend to create from our length-adjustable linkages. Taken from *http://www.thingiverse.com/thing:45203*.

Another type of chain-mail that has piqued my interest is the "Circle-Knot" design by Thingiverse user Katharos, comprised of a set of what could be best described as flower shaped elements (Fig. 7). If a way was found to make the elements of this design expand radially, a far more elegant and controllable shape-changing chain-mail would be possible. This is mentioned to showcase the variety of linkage geometries our modelling suite would ideally cover.

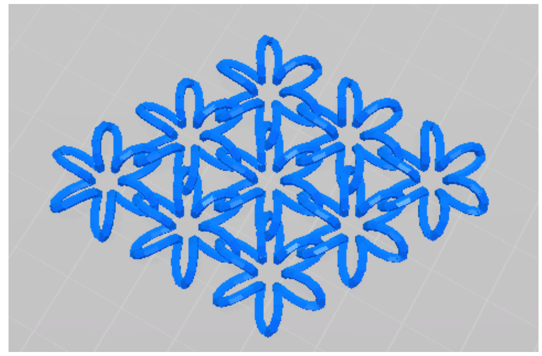

Figure 7: Katharos' *Circle-Knot* chain-mail. Taken from *http://www.thingiverse.com/thing:119729*.

VII. 3D printing

3D printing is now well established as the most accessible rapid-prototyping platform. However, that is usually all it is used for, with parts then being manufactured through milling or injection moulding once mass production has been commissioned. Due to the patient-specific nature of our product, WAM has the distinction of being a rare example of a device requiring 3D printing to create each finished article. Producing a complex device such as WAM, where actuators are embedded within a host structure comprising eventually thousands of elements and an electronic control network is distributed throughout, seems theoretically possible.

To understand the capabilities and limitations of today's 3D printers, I attended two events in November; "The 3D Printshow" (3DPS) in Islington and the "3D Printing and Additive Manufacturing Industrial Applications Summit" (AMIAS) at the Excel. The first event was a large and consumer-oriented event, with many demonstrations mostly from the companies responsible for today's desktop 3D printer market. The second was a much smaller event consisting of representatives from various industry-leading businesses where 3D printing is used - the high end customers. Two days of talks, panel discussions and networking sessions underpinned the event, with the intention of demonstrating how 3D printing is utilised in today's top engineering companies, and deciding where the future of this technology lies.

3DPS focused mainly on *fused deposition modelling* (FDM) printers, where plastic is softened via heating and passed through an extruder, which is moved around mechanically to construct an object. AMIAS was more concerned with *selective laser sintering* (SLS) where two laser beams are guided through a tank of powder, and at their intersection the temperature is great enough to fuse particles together. This is the method of choice across high-level industry owing to its superior resolution (essentially limited by the wavelength of light used - typically hundreds of nanometers), enhanced structural integrity, and the ability to print with metals. However SLS technology is currently very expensive and only capable of printing objects comprised of a single material. For our prototypes where scale is not an issue, the resolution of FDM printers should be sufficient.

One notable exhibition at 3DPS was the "Cortex Exoskeletal Cast" by designer Jake Evill (Fig. 8), relevant to WAM due to its use of X-ray imagery combined with 3D scans of the limb volume to algorithmically produce a light, thin and personalised static exoskeleton.

Figure 8: The Cortex Exoskeletal Cast by Jake Evill.
http://jakevilldesign.dunked.com/cortex

In a WAM exoskeleton, shape changing material would only be necessary in a small area around the joint, and could in fact prove dangerous if activated elsewhere. However, it may be necessary for the smart material to be bound to a static structure extending along the length of the surrounding bones to provide adherence and greater force moments, and a structure similar to the Cortex could be very effective here.

A relevant highlight from AMIAS was a talk from IBM's Veena Pureswaran discussing a recent IBM executive study [11] on the effect three emerging technologies are predicted to have on global product supply chains; 3D printing, intelligent robotics and open source software architecture. Predominantly economic in nature, the report stressed that the three technologies used in combination will result in a new manufacturing paradigm set to pose a threat to conventional industry models in the coming decade. This agrees well with the likely eventual business model for WAM, where the product is highly individualised for each patient and their disability so, depending on demand, it seems localised manufacturing would be preferable. That such business strategies are projected to gain momentum in the near future is reassuring.

Additionally, the emphasis on robotics combined with 3D printing for production of advanced products hints at how WAM construction may be automated further down the line. Our initial prototypes will be large enough for each component to be assembled by hand, with miniaturisation to follow once proof-of-concept has been established.

The RepRap project is an initiative started in 2005, with the aim of producing an open source 3D printer capable of printing copies of itself. Currently, the printers are capable of using FDM to print their own plastic components, and the project seems now concerned with how the printers may produce their own electronic components.

"A complete cycle electronics assembly machine would be an amazingly awesome and marvellous thing."

- Anon, http://reprap.org/wiki/Automated_circuitry_making

The project has identified a number of ways RepRap could be modified to this end, notably using an extruder to print molten Field's metal, which has a melting point of $62^{o}C$, using a CNC milling head in place of the extruder, and the development of a "pick and place" head. The latter seems to be the most promising approach for us, where desired circuitry components are stored to the side of the print bay and a robotic arm is used to position them. It is not inconceivable that we could build a hybrid pick and place 3D printer to produce plastic WAM structures with actuators embedded inside. Such machines are likely to appear soon if IBM's assertion about the merging of 3D printing and robotics is correct. The specifics of this faction of our work cannot be worked out until we have a better idea of the final form our actuators will take.

To prepare for when significantly modified printers become important in our project, and to aid in both the prototype construction and development of a chain-mail modelling suite, I built a RepRap Prusa i3 based on blueprints available freely from the RepRap project. Parts were printed at UCL and the remainder ordered online. The majority of the parts were purchased from separate suppliers, and I tried to build up from the "raw elements" as much as possible in order to both economise and to gain a thorough understanding of the printer's design, construction and operation. The printer is now complete and can be seen in Figure 9 printing a cube.

The aim is now to print as many chain-mail designs as possible to identify the effect linkage geometry has on flexibility. Such investigation will inspire the mathematical modelling, so that we may ultimately determine the optimal design for WAM.

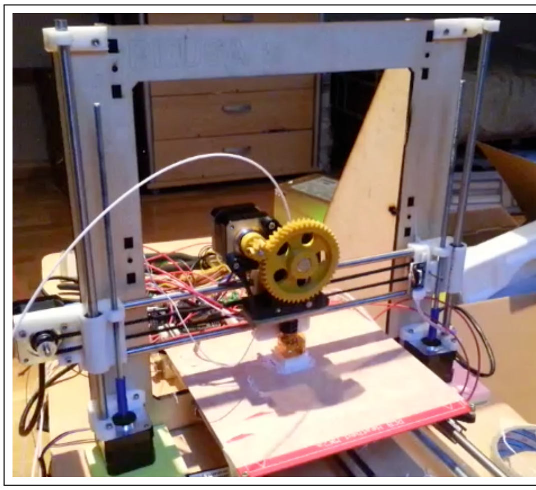

Figure 9: The RepRap Prusa i3 built for prototyping dynamic chain-mail linkages.

VIII. Summary

- Modelling will play a critical role in developing the optimal structure underpinning WAM, and provide a framework through which the product can be optimised for individual patients and their disabilities.
- OpenSIM has been identified as the software of choice for the musculoskeletal end due to its open-source architecture. The inclusion of total limb volume on top of the MS model is a modification we will need to make, and we must find a means for translating the WAM design into a dynamic object compatible with OpenSIM.
- No CAD package has been found that would be capable of modelling the WAM hierarchy from electronics through to overall shape-change, largely due to the lack of support for solid state actuators.
- Hence, I intend to produce such a system based on rigid body dynamics and differential geometry, implemented in C++ and OpenGL. Timeline: 6 months.

- Shape-changing within WAM would be best accomplished through individual elements being able to expand or contract across the surface of the skin. Further modelling is needed to determine how such expansion and contraction would drive the overall shape-change from one volumetric profile to another.

- I have built a 3D printer to produce chainmail, which will be used to inform the modelling process and fabricate initial prototypes.

- I intend to produce a scaled up prototype patch of "smart chain-mail", where the linkage length (and resultant flexibility) can be electronically controlled. Nitinol springs will be used as stand-in actuators. Timeline: 3 months.

- A 3D printing pick and place machine could be used to produce chain-mail with embedded actuators.

- Whilst shape-changing material would be positioned over the joints, it should be attached to a rigid structure to continue WAM along the remainder of the limb, similar to the Cortex Exoskeletal Cast.

References

[1] Nick Tyler and Xenia Karekla. Potential materials and their mechanical properties for an exoskeleton walking support. 2012.

[2] Anna-Maria R McGowan, Anthony E Washburn, Lucas G Horta, Robert G Bryant, David E Cox, Emilie J Siochi, Sharon L Padula, and Nancy M Holloway. Recent results from nasa's morphing project. In *SPIE's 9th Annual International Symposium on Smart Structures and Materials*, pages 97–111. International Society for Optics and Photonics, 2002.

[3] MH Love, PS Zink, RL Stroud, DR Bye, and Charles Chase. Impact of actuation concepts on morphing aircraft structures. *AIAA Paper*, 1724:2004, 2004.

[4] John S Flanagan11, Rolf C Strutzenberg, Robert B Myers, and Jeffrey E Rodrian. Development and flight testing of a morphing aircraft, the nextgen mfx-1. 2007.

[5] Stephen Daynes and Paul M Weaver. A morphing trailing edge device for a wind turbine. *Journal of Intelligent Material Systems and Structures*, 23(6):691–701, 2012.

[6] Lorenzo Lignarolo, Charlotte Lelieveld, and Patrick Teuffel. Shape morphing wind-responsive facade systems realized with smart materials. In *Adaptive Architecture Conference*, pages 3–5, 2011.

[7] Mauricio Morales-Beltran and Patrick Teuffel. Towards smart building structures: adaptive structures in earthquake and wind loading control response–a review. *Intelligent Buildings International*, 5(2):83–100, 2013.

[8] Michael A Evans and Gwendolyn A Watanabe. Radially expansible vascular prosthesis having reversible and other locking structures, January 20 1998. US Patent 5,709,713.

[9] Sarah F Gibson. 3d chainmail: a fast algorithm for deforming volumetric objects. In *Proceedings of the 1997 symposium on Interactive 3D graphics*, pages 149–ff. ACM, 1997.

[10] Henry Crapo. Structural rigidity. *Structural Topology*, 1(26-45), 1979.

[11] Paul Brody and Veena Pureswaran. The new software-defined supply chain - preparing for the disruptive transformation of electronics design and manufacturing. 2013.