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Mechanical Design and Theoretical Analysis of a Four Fingered Prosthetic Hand Incorporating Embedded SMA Bundle Actuators

Kevin T. O'Toole, and Mark M. McGrath

***Abstract*—**The psychological and physical trauma associated with the loss of a human limb can severely impact on the quality of life of an amputee rendering even the most basic of tasks very difficult. A prosthetic device can be of great benefit to the amputee in the performance of everyday human tasks. This paper outlines a proposed mechanical design of a 12 degree-of-freedom SMA actuated artificial hand. It is proposed that the SMA wires be embedded intrinsically within the hand structure which will allow for significant flexibility for use either as a prosthetic hand solution, or as part of a complete lower arm prosthetic solution. A modular approach is taken in the design facilitating ease of manufacture and assembly, and more importantly, also allows the end user to easily replace SMA wires in the event of failure. A biomimetric approach has been taken during the design process meaning that the artificial hand should replicate that of a human hand as far as is possible with due regard to functional requirements. The proposed design has been exposed to appropriate loading through the use of finite element analysis (FEA) to ensure that it is structurally sound. Theoretical analysis of the mechanical framework was also carried out to establish the limits of the angular displacement and velocity of the finger tip as well finger tip force generation. A combination of various polymers and Titanium, which are suitably lightweight, are proposed for the manufacture of the design.

***Keywords*—**Hand Prosthesis, Mechanical Design, Shape Memory Alloys, Wire Bundle Actuation.

I. INTRODUCTION

THE loss of a limb can severely impact on the quality of life of an amputee and thus render the most common every day tasks difficult if not impossible. Over the last few decades, major progress has been made in the development of intelligent prostheses which can at least partially fulfil the requirements of the missing limb. The hand is viewed as one of the most important parts of the human body as it allows for adaptation, exploration, prehension, perception and manipulation [1]. Traditionally, artificial hand designs have tended to be bulky, heavy and noisy due to the use of electro-mechanical actuators [2][3][4]. As a result of the problems inherent with this type of actuation, designers have been adapting various other actuation techniques for use in their place.

The main drivers for the design proposed here is the development of a hand exhibiting high dexterity and functionality whilst being lightweight and easy to manufacture/assemble. Shape memory alloys (SMA's) have been shown to exhibit a high force-to-weight ratio which qualifies them as being suitable for many biomedical applications. This good force-to-weight ratio, coupled with large contraction and expansion capabilities, makes them a key technology for exploitation in the actuation of artificial hand designs. Various groups have successfully attempted to produce working hand designs using SMA actuation [5][6]. However, designs to date have relied on extrinsic location of the SMA bundles leading to limitations in their use. Designs to date have also exhibited relatively small finger tip forces [5] rendering them obsolete for use in many gripping tasks. A guide to the current state-of-the-art can be found in section III of this paper.

A biomimetric mechanical design of an artificial hand exhibiting twelve degrees-of-freedom and actuated using embedded SMA bundles is proposed. This mechanical design aims to progress the state-of-the-art through the use of intrinsic actuation using SMA bundles. The proposed design includes embedded SMA actuators to manipulate the index, middle, ring and little finger. The approach taken is one of modularity, allowing the artificial hand to be assembled and disassembled with relative ease. This offers many advantages to the end user, for example, ease of replacement of SMA wires in the event of failure and the ability of the prosthesis to be used for many different levels of amputation. These features of the design can only lead to enhanced user confidence in the prosthesis solution. A combination of various polymers and Titanium are proposed as the materials of choice for the manufacture of the design included. Due to the inherent weight restrictions imposed by the measurements of the human limb, optimal material sizing is of fundamental importance at the design stage. Finite element analysis (FEA) tools are used to check the structural integrity of the hand at various high load bearing locations of the prosthetic hand structure. This resulted in a structurally sound design which yields improved comfort benefits to the end user. A mechanical analysis of the finger design was carried out to establish the theoretical finger tip forces generated. These forces will be compared against the actual forces generated by a working human limb upon the completion of the manufacturing stage (ongoing work).

It must be mentioned at this point that the current design does not include the design detail of the thumb. The rationale for this is that the thumb must generate much higher forces than any other finger when performing certain gripping actions due to the thumb opposing the total force generated by the four fingers. This thumb behaviour is prevalent in common grip types such as a pinch grip, power grip and tripod grip. SMA materials are not suitable for this

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application and as a result, an alternative actuator is currently being characterised for this application. This is the focus of ongoing work and on completion will be integrated with the current design.

II. SMA BUNDLE BEHAVIOUR & CHARACTERISTICS

SMA's consist of a group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to an appropriate thermal procedure [7]. At room temperature, the material is in a Face Centred Cubic (FCC) Martensitic state and can be easily deformed. The material can be heated by applying a voltage drop across the wire and thus causing current to flow. This causes a resistive heating effect known as joule heating. As a result, the crystal structure changes to a more compact Body Centre Cubic (BCC) form as the phase changes from Martensite to Austenite [8]. This cycle is coupled with considerable hysteresis during heating and cooling. The wire must be exposed to a 'relaxation force' if the contraction/extension cycle is to occur. The 'relaxation force' is necessary to assist the deformed SMA to return to its original shape and length.

As a result of the substantial hysteresis (due to energy dissipation) that occurs on the heating/cooling cycle, accurate control of SMA's can be difficult. Previous work carried out by this group established the transient and steady-state strain/force behaviour of suitable 150μm diameter SMA bundles consisting of up to fifteen individual Nitinol SMA wires [9]. It was shown that as the energising current is lowered, the SMA's exhibit reduced hysteresis between the heating and the cooling cycles. However, below 55% of the maximum recommended current (MRC), the SMA's exhibit behaviour which is unreliable and therefore unsuitable for actuation purposes [7]. A summary of the transient and steady-state analysis testing is outlined hence forth.

The transient behaviours of the human hand and the SMA bundle actuators are compared through measurement of their respective time-constants. The heating time constant of the SMA bundles increases as the energising current is decreased from 100% to 55% of the MRC. As the number of wires in the SMA bundles is decreased, the heating time constant increases due to the reduction in resistance in the series circuit which supplies the energising current. A bundle of fifteen 150μm SMA wires exhibited a heating time constant of approximately 0.5 seconds, which equates favourably with the measured time constant of an average human hand during normal gripping activity of 0.405 seconds. The cooling time constant remains similar for differing bundle wire volumes due to the atmospheric cooling conditions to which they were subjected. It was shown that this time constant was approximately 1.5 seconds. It is envisaged that the use of forced cooling techniques will improve the performance of the actuators during the cooling stage of the cycle. Improved controllability of the actuators will result if the cooling cycle behaviour is similar to that during the heating cycle.

The force generated by the SMA bundles decreases as the number of SMA's in the bundle decreases. This force also decreases as the current is dropped from 100% to 55% of the MRC. Below 55%, the force generated is minimal due to the phase change from Martensite to Austenite not occurring due to the lack of thermal energy. The maximum force generated at 100% MRC using fifteen SMA wires in a bundle is approximately 52N, which is 84% of the maximum grip force measured in the strongest phalanx (middle distal) of the human hand. Due to the high force generation, suitable heating/cooling time constants, and minimal weight and size of the SMA wires, SMA bundles can be deemed highly suitable for use in the actuation of an artificial hand.

III. CURRENT STATE-OF-THE-ART: A BRIEF REVIEW

Early designs of artificial limbs were large and bulky as a result of using traditional actuators such as electromechanical motors. While DC motors provided prosthesis design with significant torque to simulate the strength generated by the human hand, many compromises were necessary within the design itself. Upper limb prostheses tended to be bulky, heavy and noisy. Examples of state of the art designs using DC motor actuation are The NTU Hand [2], The DLR Hand [3], and The Robonaut Hand [4].

Underactuated mechanisms for use in prostheses designs were developed by various groups in an attempt to overcome some of the disadvantages associated with these early designs. Some of the more successful underactuated hand designs were developed [10][11]. Underactuated mechanisms lead to an adaptive grasp, and provide compliance and simplicity in control, but reduce the manipulability of the grasp and the dexterity of the hand in general [12].

Experimental trials were carried out using non-traditional actuation techniques such as Shape Memory Alloys (SMA's), Electro-Magnetics, Mechano-chemical Polymers, Conducting Polymers, Piezoelectric and Magneto-strictive materials [13][14] due to the problems associated with using traditional actuation methods in prosthesis design. Of these methods, only SMA's have been used extensively in a vast number of applications including robotics and medicine [5]. SMA's have been used extensively in robotic applications in the field of biomedical engineering as they exhibit muscle like properties [8][15]. SMA's, owing to their small size and excellent force-to-weight ratios, provide an opportunity to facilitate additional degrees-of-freedom in prosthetic designs [9]. The most widely known SMA actuated upper limb prosthetic device is the Hitachi Ltd Hand developed in 1984 [16]. The Hitachi Ltd Hand included a forearm, weighed 4.49kg and was 69.85cm long. It had a load capacity of approximately 2kgf. The Rutgers Hand, a SMA actuated hand which comprised of five fingers and twenty degrees-of-freedom was developed in 2002 [5]. This hand has the ability to produce a 6.67N finger tip force. Tendons consisting of tin braided Teflon material were used to simulate the tendons in a human hand. Each tendon was attached to an SMA muscle bundle which was located in a similar position to that of the radius and ulna in the human arm. The tendons run through the middle of the wrist spherical joint. Each finger has two artificial muscle bundles, one for flexion and the other for the necessary recovery force. The drawback of this design is that the SMA's are not embedded intrinsically within the hand, therefore limiting the fit for different degrees of amputation.

A biomimetric approach to SMA-actuated hand prostheses design has been adopted since 2005 by various groups. A four degree-of-freedom finger which closely mimics the kinematics and size proportions of the human finger was subsequently developed in 2006 [6]. SMA driven tendon wires which are directly attached to the finger structure are used, simulating the natural tendons in a human hand. Also in 2006, work was carried out which described an array of biological muscles employed to drive a five fingered hand [17].

The continued development of non-traditional actuation methods has led to artificial hand designs which closely mimic the human hand. In 2007, a study characterising the transient response of SMA actuators was carried out as a precursor to the current paper by this group [9]. As a result of this work, the selection of suitable SMA bundle sizes and SMA wire diameters, which could mimic the transient and steady-state muscle performance of an average human hand, were determined. In spite of these recent advances, major obstacles still exist. Some of these problems include but are not limited to; the miniaturisation of auxiliary components, the output force of actuation, power supply and power storage [12]. Further developments will no doubt render SMA's as highly suitable actuation solutions for artificial hand prostheses design.

IV. MODULAR MECHANICAL DESIGN

This section outlines the proposed modular nature of the mechanical design of a four-fingered, twelve degree-of-freedom prosthetic hand (Fig. 1) with a mass of approximately 400g. Intrinsic actuation is to be provided for through the use of embedded SMA bundle modules. The basis for the modular design presented here is to cater for the isolation of the individual SMA bundles for ease of maintenance and replacement where necessary. The desire to develop a biomimetic hand placed limitations on the maximum dimensions of the hand. The design can be categorised into five distinct areas, namely; A. The embedded SMA actuation system, B. The finger design, C. The palmar structural design, D. Modularity, and E. Mechanical analysis.

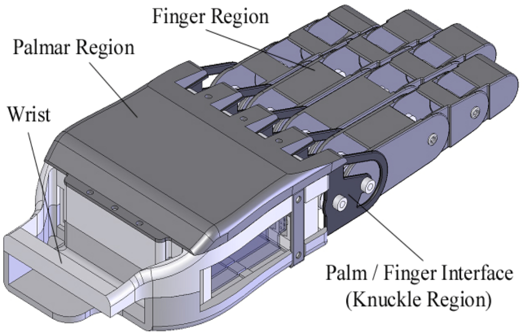

Fig. 1 Assembled Mechanical Design

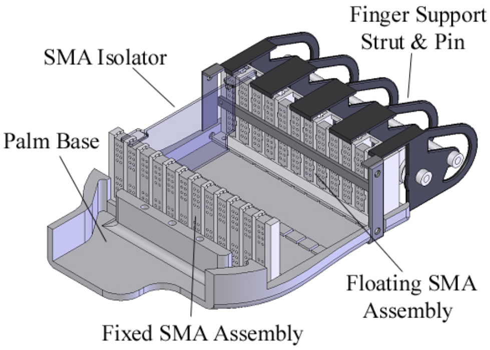

Fig. 2 Palmar Region

A. SMA Actuation System (Embedded)

This novel design approach mounts each SMA bundle into the palm of the prosthetic hand due to the restrictive limitations of previous designs which located the SMA bundle actuators in the forearm [5]. The advantage of this design is that the artificial hand module can be used for different degrees of amputation. The actuation system consists of two module-block holders located within the palmar area of the design. Each block is designed to house twelve individual SMA modules to which the SMA wires are attached. Each module block is separated by a distance of 56mm from face to face, and is 90mm in width (Fig. 2). The module-block holder located at the wrist end of the palm is designed to hold the SMA modules in a fixed position. The module-block holder located at the finger end of the design allows the SMA modules to slide back and forth under the forces generated during heating and cooling of the SMA wires (Fig. 4). Linear sliding motion is ensured through the provision of a series of shallow inlets within the module-block holder. The material selected for both the module-block holder and the SMA modules is PTFE (PolyTetraFlouroEthylene) owing to its low coefficient of friction, high strength, high heat resistance, good electrical resistance and ease of molding. Each SMA module has a sixteen hole array to which the SMA wires can be anchored. Previous work by this group has established the optimal SMA bundle sizes required to produce the various forces of each individual joint in the hand [9]. The SMA's are distributed as evenly as possible throughout the SMA modules to ensure that maximum linearity in the sliding motion is achieved.

Eleven PTFE isolators (Fig. 2) are fitted between each SMA bundle within the palmar region of the hand. The purpose of these are to isolate the heat generated by each SMA bundle as they are energised by electrical current. This will allow for enhanced control of the internal air temperature within the palm thus facilitating faster response times and improved control over actuator behaviour. The isolators will also serve as a suitable mechanical framework on which to house temperature sensors when controlled actuation is implemented in future work.

A spring system/arrangement assembly is located on a platform above the PTFE isolators (Fig. 3). This arrangement is essential so as to provide the necessary 'relaxation' force to return the SMA's to their original length. The spring system/arrangement consists of twelve springs, one for each dynamic SMA module. A Nickel artificial tendon is attached to the back face of the sliding SMA module where a specifically designed point of connection is provided. The tendon is guided around an 8mm diameter pulley and attached to the opposing spring, thus completing the circuit. The 8mm pulley is attached to a larger 16mm pulley adjacent to it (Fig. 6). The rotation of the smaller pulley due to the friction between the Nickel tendon and Mild Steel pulley induces rotation of the larger pulley at the same velocity, delivering the same torque. During actuation of the SMA bundles at an average of 6.5% strain, the SMA wires contract by approximately 3.9mm (total length = 60mm). This linear movement results in pulley angular translation of 56^{o} (Fig. 10).

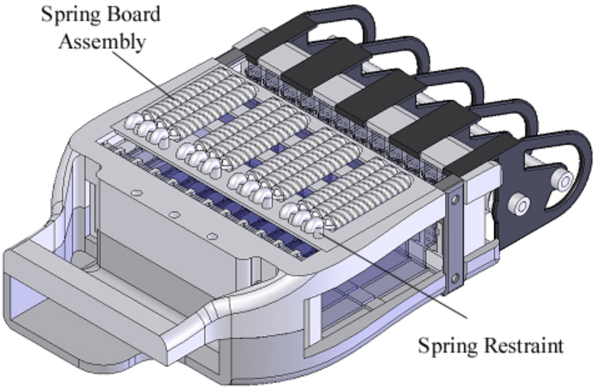

Fig. 3 Spring Board Assembly

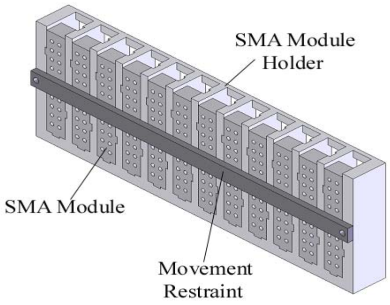

Fig. 4 Floating SMA Assembly

B. Finger Design

Each individual finger consists of a proximal, an intermediate and a distal phalanx which are linked together mechanically (Fig. 5). The lengths of each individual phalanx are consistent with that of an average adult human finger. Each phalanx displays a constant thickness of 20mm over almost its entire length. Each finger is tapered slightly from the metacarpophalangeal (MP) joint to the tip of the finger in keeping with the biomimetric approach to the design.

The outer wall of each phalanx consists of 2mm thick PEEK (PolyEtherEtherKetone) polymer shaped appropriately, which is reduced to 1mm thickness in close proximity to the areas of rotation, where the phalanges overlap.

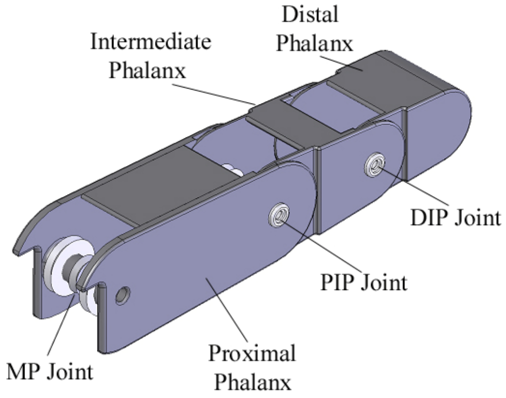

Fig. 5 Index Finger Assembly

The individual finger joints consist of cylindrical Titanium pins with a series of pulleys mounted on each. Each MP joint consists of three Mild Steel pulleys. The centrally located pulley has a custom designed keyway which permits this pulley to rotate the phalanx when actuated. Passive pulleys, 16mm in diameter, lie either side of this central pulley (Fig. 6). The passive pulleys are used to support the artificial tendons that are destined to actuate the other joints, namely, the Proximal-Interphalangeal (PIP) joint and the Distal-Interphalangeal (DIP) joint. As mentioned in Section III (A), the pulleys used in the SMA bundle/spring connection rotate 56^{o}. This angle must be increased to mimic the angular rotation capacity of the human hand, which is approximately 80^{o}. A pulley system with a diameter ratio of 2:1 is employed to increase the rotational advantage, delivering a potential rotational angle of approximately 112^{o}. Mechanical stops are incorporated to limit this movement to the required 80^{o}.

The PIP joints (Fig. 6) are designed in a similar fashion to the MP joints, however, they consist of only two pulleys rotating around the central rotational axis. One of these pulleys is active and has a similar custom designed keyway to allow for phalangeal rotation. The remaining pulley is passive and is used to support a tendon during actuation of the DIP joint (Fig. 7).

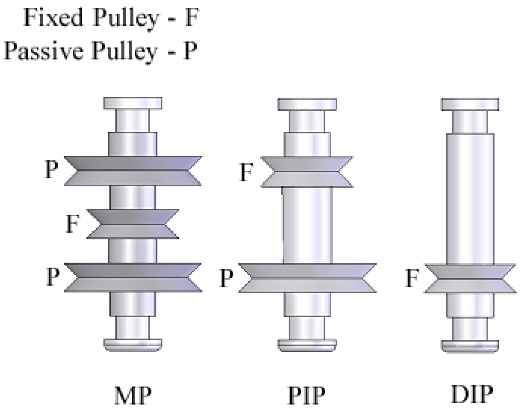

Fig. 6 Finger Joint Pulley Configurations

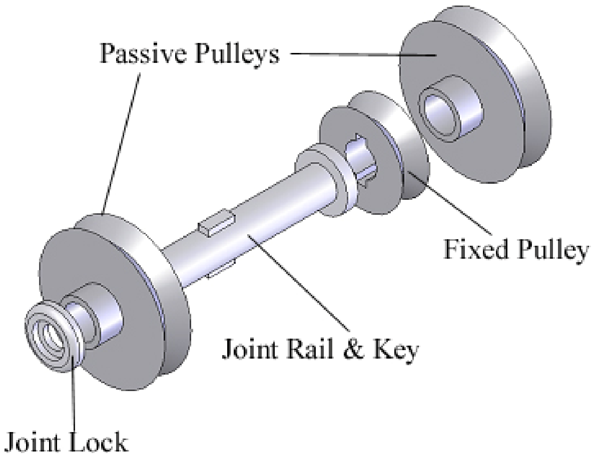

Fig. 7 Metacarpophalangeal (MP) Joint Exploded View

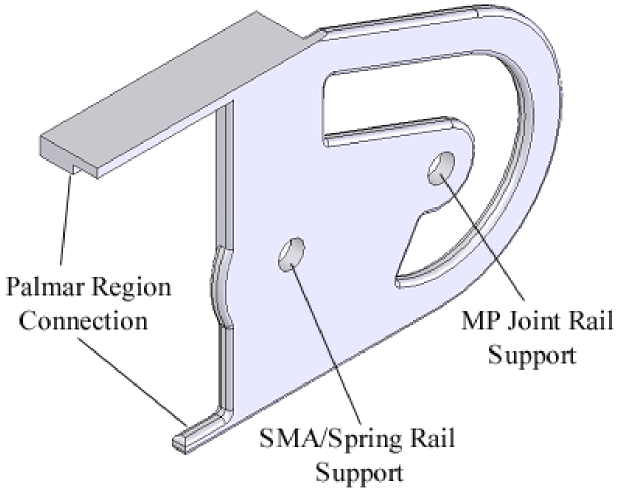

Fig. 8 Palm-Finger Connection Support Strut

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A natural mechanical stop limits the rotation of the intermediate phalanx as it approaches 90^o. The DIP joint consists of only one pulley which is active with a similar keyway which engages the rotation when required. As with the PIP joint, a natural mechanical stop limits the rotation to approximately 90^o.

C. Palmar Region Structural Design

The palm region mechanical arrangement consists of four easy-to-assemble structural entities. The SMA actuation block is encased in a PEEK casing, consisting of separate, custom designed, upper and lower halves. Secure joining of these halves is achieved through the use of three M4 screws at the rear of the hand, as well as custom designed PEEK connection devices located on each side of the hand towards the finger area (Fig. 8). These two devices ensure a rigid, secure connection between the upper and lower halves of the palm structure. A series of grooves and notches, on the bottom half of the palm structure, allow for guidance of each module block holder into the correct location. This arrangement also ensures that the SMA isolators can be secured into the correct position. The module block-holders and the isolators are secured in place through the joining of the top and bottom halves of the palm structure. The fingers are connected to the palm via a series of five rigid finger support struts.

Slots are located on the top and bottom half of the palm structure specifically to allow for ease of integration. The finger support struts contain two 3mm diameter holes which allow the Titanium pulley support rails to pass through. The rails are secured at each end using appropriate threaded fixings. A suitable dorsal covering is used to mimic the contours of the dorsal side of the human hand and to provide a method of locking the structure together securely using a series of screws (Fig. 1).

At the rear end of the design, a substantial notch has been removed from the bottom half of the palm region which is necessary to facilitate the positioning of a thumb joint (Fig. 11).

D. Modularity

The design of a modular mechanical framework is essential in order to allow for easy replacement of SMA wires whenever it should become necessary. The design presented here facilitates this by allowing the removal of the internal SMA block-holders through the underside of the hand. To facilitate this, the three assembly screws located at the rear of the hand, near the wrist, and the two palm connectors located on either side of the hand, must be removed. The SMA separation restraints must then be unlocked and removed. The palm base can then be separated from the top half. The SMA holders (Fig. 9) can then be slid out of their respective blocks allowing for easy replacement of the SMA wires where necessary.

Further advantages of taking a modular approach to the design of the mechanical framework can be found in the manufacture and general assembly of the hand. Each separate section is intended to be manufactured individually and subsequent assembly can then proceed stage by stage. The SMA blocks and holders are to be assembled initially. These can then be fitted into the palm base, which can then be built up around the SMA dynamical area. Each individual phalanx can be manufactured and assembled separately, then joined together to form complete fingers. The fingers are subsequently joined to the palm structure via the palm/finger interface (knuckle region).

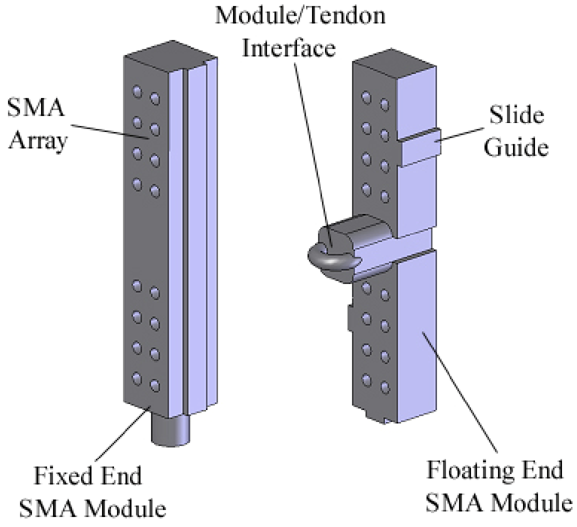

Fig. 9 SMA Modules

E. Mechanical Analysis

Rotation of the phalanges is achieved through a system of miniature cables and pulleys. The SMA length is limited to 60mm due to the size restrictions of the palmar region. The contraction length of the SMA is relative to its full length when heated (between 5%-8% of the total length). The intrinsic location of the SMA bundles within the palm region of the hand leads to smaller contraction lengths when compared with previous designs featuring extrinsically located SMA bundles [5]. The contraction length of the chosen SMA wires is 3.9mm (6.5% of 60mm length). This length is lower than the critical length necessary to rotate the pulleys through the required actuation angle. A pulley arrangement was designed producing a rotational advantage of two. This allowed the pulleys to rotate to the desired angles.

The SMA blocks are connected directly to the 'relaxation' springs via an 8mm diameter pulley which is directly coupled to a 16mm diameter pulley. The 3.9mm movement results in a rotation of approximately 55° of the two pulleys. The 16mm pulley is in turn linked to an 8mm pulley located at the joint of movement. The ratio of 2:1 results in the smaller pulley rotating through 110° which is greater then the maximum angular rotation of any joint in any human finger. The rotation is limited by a mechanical stop built into the design at each joint. However, as a result of the increased angular rotation and also the belt slippage which is typical in such an arrangement, the torque value and ultimately the force exerted by the finger tip, is reduced.

$$P = T_1\omega_1 = T_2\omega_2 \qquad (1)$$

The angular velocity of the artificial finger joints is 2.48rads/s, which is slightly faster than that of the human hand, which has an average angular velocity of 1.57rads/s [9]. The dynamics of the pulley system (fig. 10) were determined theoretically using (1).

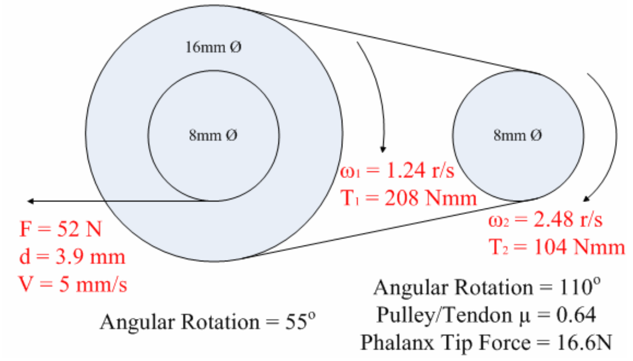

Fig. 10 Rotational Analysis

F. Thumb Consideration

In the design presented, the thumb is considered an independent mechanical module and as such, is not being considered as an integral part of this paper. It will be detailed in future work incorporating alternative actuation methods. Due to the high forces necessary in the thumb joint (i.e. when opposing the forces generated by all four fingers in certain grip types), SMA actuation is not sufficient. For example, in order to extract a plug from a socket, 20-30N of pinch force is required. The thumb must produce a force of this magnitude to oppose the other four fingers of the hand in order to maintain a sufficient pinch grip on the plug. An alternative actuation system allowing for higher force generation is currently being characterised for actuation of the thumb and accompanying joints which will be added to the current mechanical design at a future stage. As a precursor to this addition, an area located at the rear of the hand has been selected as the thumb placement area (fig. 11). Material has purposely been removed from the palm base to facilitate the thumb placement.

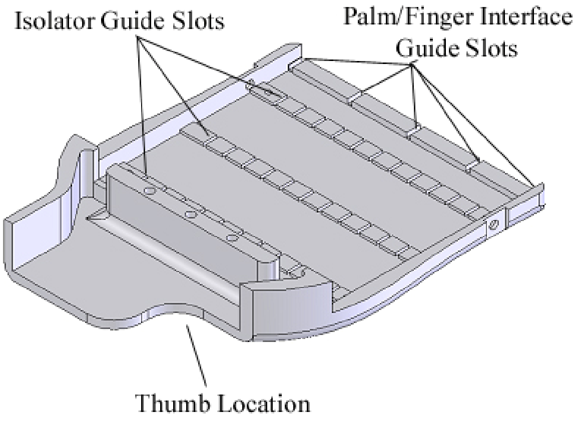

Fig. 11 Palm Base & Thumb Location Cut-out

The design of the thumb is currently on-going and will be detailed in future work following testing/characterisation of the current design.

V. MATERIAL SELECTION & STRUCTURAL INTEGRITY

The selection of appropriate materials for the manufacture of the prosthetic structure is critical. The major factors influencing decisions in the different areas of the design include the following: strength, heat resistance, ease of manufacture/molding, specific gravity, electrical conductivity, costing and the friction. PTFE and PEEK were selected as the most suitable materials for the SMA module structure. PTFE is selected for the SMA holder blocks due to its low co-efficient of friction (CoF) with itself and crucially, with the stronger PEEK polymer. This allows the SMA holders to move back and forth with minimal resistance during SMA contraction and expansion.

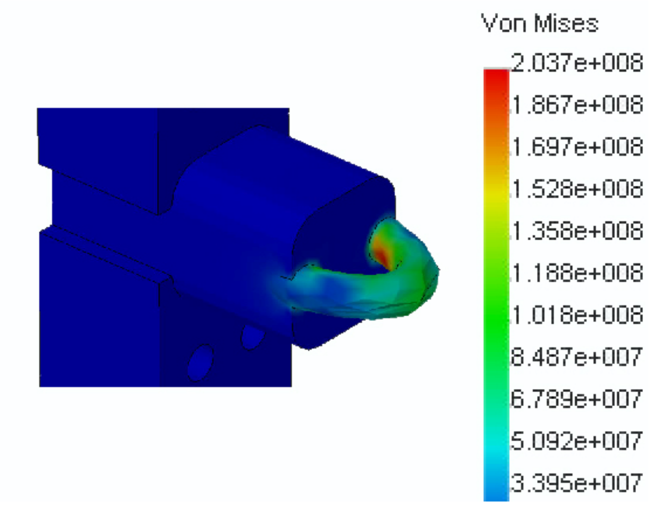

Fig. 12 PTFE Module/Tendon Interface Failure

Finite Element Analysis (FEA) testing of the structure has shown that PTFE has insufficient strength to act as a suitable SMA holder due to its relatively low tensile and shear strengths. As a result, PEEK was selected as an alternative due to its high strength in the critical SMA holder/tendon linkage joint (fig. 12). PEEK also exhibits a high melting point which is necessary to resist the heat generated by the individual SMA wires. Critically, it demonstrates a high electrical volume resistivity ensuring the energising current cannot pass between individual SMA wires causing short circuit failure. Lightweight PTFE sheets are chosen to isolate and facilitate heat removal during SMA excitation.

PEEK is the material of choice for the palm/finger interface within the knuckle region. Optimal material thickness has been established using FEA testing (fig. 13). PEEK has been selected as it exhibits a low specific gravity in comparison to steel but maintains its structural integrity under substantial loading. The SMA-Spring pulleys will be manufactured from Mild Steel. Nickel will be used in the manufacture of the artificial tendons as it exhibits a relatively high CoF in contact with Mild Steel.

PEEK is prevalent in the palmar structure due to its high melting point, good chemical resistance and high modulus of elasticity. From a manufacturing point of view, it can be easily molded to produce the desired irregular shapes. A Titanium bonding connector will be used to secure both halves of the palm structure together. Titanium has a greater shear strength (550MPa) compared to PEEK (55MPa) and can resist the separation forces generated by the opposing halves of the structure.

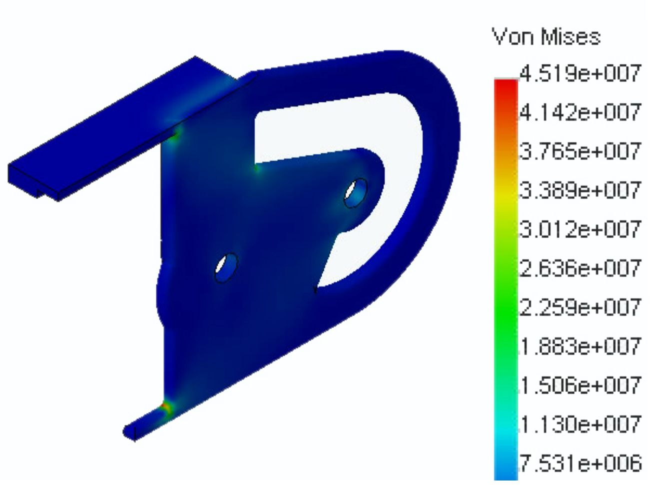

Fig. 13 PEEK Palm/Finger Interface Test

Titanium is also used for the spring restraint due to its high shear strength. The spring assembly board however can be PEEK as it is not subjected to similar high shearing forces.

PolyVinylChloride (PVC), with a density lower than that of PEEK, is selected for each individual phalangeal wall due to its adequate strength in resisting typical grasp forces which will be experienced by the finger structure. FEA was employed to establish optimal finger surface wall thickness. Each active pulley (i.e. those which deliver rotation of an individual phalanx) is to be manufactured from Mild Steel. The passive pulleys are to be produced from PTFE as it exhibits a low CoF in contact with Nickel, therefore allowing the tendons to move back and forth with minimal resistance. Rotational joints are to be manufactured from Titanium due to the high shear strength, as outlined previously.

VI. CONCLUSION & FUTURE WORK

A novel mechanical hand design incorporating embedded SMA bundle actuators within the palmar area was presented. The design allows for a 12 degree-of-freedom range of movement. The design is based on a modular approach with an emphasis on ease of assembly, and ease of replacement of SMA wires. By locating the SMA wires within the palmar region, the artificial hand can be used as either an independent hand prosthesis, or alternatively, in conjunction with a modular prosthetic wrist and forearm to form a complete lower arm prosthetic solution. The SMA actuated prosthesis offers a more comfortable, more lightweight and quieter solution when compared to the more traditional electro-mechanically actuated prostheses. SMA actuated designs to date have relied on mounting SMA bundles within the lower arm to actuate the hand, thus eliminating their potential for use in less severe prosthetic solutions.

The mechanical design presented will be manufactured from a combination of high strength polymers such as PTFE & PEEK and low density metals such as Titanium. High strength polymers have the advantage of being easily machined and lightweight when compared to metals for the same purposes. Where applicable, finite element analysis was carried out to ensure that dimensions chosen are suitable for the range of forces to which they will be exposed. Optimal material/dimensional decisions were made on the basis of the results of these tests. This resulted in a structurally sound design. The mechanics of the finger movement under actuation from the SMA wire bundles was analysed resulting in a maximum potential phalangeal tip force of 16.6N, which is approximately 30% of the average maximum finger tip force of the strongest (middle distal) phalanx within the human hand. This range of forces will allow the end-user to complete everyday tasks comfortably such as inserting a plug into a wall socket, gripping and turning a key in a door, gripping a drinks container or using an eating utensil such as a fork [18]. It will not, however, for example provide enough force to use a fork or to extract a plug from a socket [18]. Previous extrinsically actuated models have generated a maximum finger tip force of 6.67N [5] which severely restrict the range of use of the prosthesis.

Immediate future work will concentrate on the manufacture of the current design in order to compare the actual mechanical characteristics against the theoretical. This work will be carried out in tandem with the characterisation and implementation of a suitable pneumatic actuator for actuation of the thumb to complete a five-fingered biomimetric artificial hand. Space has been allocated in the mechanical design presented here for the thumb design to be implemented. The mechanical prototype will serve as a platform for the characterisation and implementation of various control strategies. Movement of the final prosthetic solution is to be initiated, through a purpose built adaptive controller, by myoelectric signals derived from suitable locations on the upper arm.

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