ABSTRACT
The development of diagnostic techniques has augmented the number of operations performed in relation to resolving wrists pain. This cadaveric study obtains effective biomechanics knowledge which can be used to address the long-term surgical and therapeutic solutions related to the array of forearm medical conditions by considering the loadsharing mechanism of cadaveric specimens subjected to a multiplanar loading of the hand. Kinetic understanding of the load bearing response of the lunate, scaphoid, ulna and radius in response to a three-dimensional load is given. The lunate and scaphoid were exposed by dissection and a rosette strain gauge is bonded to each, in addition gauges are attached to the radius and ulna. A custom built rig was developed which allows a loading profile to be applied to each phalanx of cadaveric forearm specimens, and the relative force transmitted through the lunate and scaphoid and the ulna and radius to be monitored.

KEY WORDS
Wrist Joint, Load distribution, Cadaveric strain gauging

1. Introduction
Wrist pain is a widespread problem, causing a profound effect on the hand function with a significant personal and social impact. Rheumatoid arthritis patients suffer significant deterioration in ‘grip strength’, which can render even the simplest tasks such as turning a doorknob extremely problematic. The evolution of diagnostic techniques such as magnetic resonance imaging (MRI) and arthroscopy has increased the number of operations performed in attempting to ease painful wrists. Key to this development is a lucid understanding of the load transfer characteristics through the wrist. Currently, in the vast majority of load transfer analysis performed on cadaveric arms, the applied loads on the metacarpals is planar. The specimen is typically rigidly fixed in a tensile test machine and exposed to a compressive axial force [1-5] or alternatively a specially designed rig applies a planar force [6,7]. Physiological loading of the hand is multiplanar, and absolute axial loading of the metacarpals seldom occurs [8]. Kinetic understanding of the load bearing response of the lunate, scaphoid, ulna and radius in response to a three-dimensional load has not yet been achieved. If an understanding of the load transfer characteristics in the forearm during routine tasks is to be obtained, a more complex loading regime, which accurately mimics grip strength, is required. In this study a custom built rig has been developed which allows a loading profile to be applied to each phalanx of cadaveric forearm specimens, and the relative force transmitted through the lunate and scaphoid and the ulna and radius to be monitored.

2. Methods

2.1 Grip Strength load profile
In order to obtain realistic grip strength loading conditions to implement in the cadaveric study, grip strength trials were performed on 50 volunteers. An eight-camera, 120hZ VICON motion analysis system (Oxford Metrics, Oxford, UK) was used to evaluate wrist joint kinematics during a series of grip strength assessments. This motion analysis system is used in conjunction with a whole-hand retro-reflective marker system [9]. External loads applied to the five digits were measured concurrently using a custom-built grip strength tool (illustrated in figure 1). Each six-component transducer measured the forces \( F_x \), \( F_y \) and \( F_z \) and the moments \( M_x \), \( M_y \) and \( M_z \) for each individual digit. The three-dimensional external load contribution of each metacarpal to the overall grip strength was derived. Maximum grip strength is measured for three wrist postures: neutral position, position of
maximum flexion and position of maximum extension. The average of three measurements was taken for each joint position (table 1).

2.2 Cadaver arm preparation

A tissue bank of six normal and six rheumatoid fresh frozen human forearms were obtained for the study. Each forearm underwent a series of MRI scans to define anatomical details. The forearms were stripped of soft tissue, leaving the skeletal and ligamentous structures and joint capsules intact. The interosseous membrane was also left intact, Birkbeck et al. [10] among others showed that disruption of the interosseous membrane alters the normal pattern of load transmission through the forearm. The dorsal non-articular surfaces of the lunate and scaphoid were further exposed by dissection and a rosette strain gauge was bonded to each (figures 2 and 3). Bonding was achieved utilising a protocol similar to that defined by Maser [6]. The bone surface is coated with a thin layer of M-bond AE-10 adhesive in order to seal the pores and provide a sufficiently flat area to allow adhesion. After this layer is dry a further layer of adhesive is added and the gauge is adhered by exerting a constant compressive force. In order to prevent seepage of liquid from the surrounding tissue the gauge is coated with general-purpose gauge coating. This process was repeated in order to adhere gauges to the proximal end of radius and ulna (figure 4).

<table>
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<th>Wrist posture</th>
<th>digit</th>
<th>Fx (N)</th>
<th>Fy (N)</th>
<th>Fz (N)</th>
<th>Mx (Nm)</th>
<th>My (Nm)</th>
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Table 1. Three-dimensional mean loads applied to individual digits in three different wrist postures. The digits are numbered 1-5, starting with the thumb.
2.3 Test Rig

A custom-designed rig was built to hold the limb securely and allow application of loads to digits. The rig, which can accommodate a range of forearm sizes, consist of a custom made bench with a worktop made from industrial grade polymer. The apparatus is described in figure 5. Forearms are potted in poly-methylmethacrylate in 90° flexion and then clamped to the adjustable back plate, such that the radius and ulna are orientated in the horizontal plane. The distal phalanges of the fingers are placed on the pads of the grip strength tool. The hand is held initially in neutral wrist extension, but can be orientated to maximum flexion and extension.

Loading is applied to each individual digit via a construct of artificial tendons. A 2.5mm diameter non-extensible cord with a Polyurethane coating is employed to replicate tendon functions of the extensors (Extensor Pollicis Longus, Extensor Pollicis Brevis, Extensor Digiti Minimi, and Extensor Digitorum) and flexors (Flexor Digitorum Profundus, Flexor Digitorum Superficialis, Flexor Pollicis Brevis and Flexor Pollicis Longus). Extension/Flexion of wrist has been simplified by including only an approximate representation of the Flexor Carpi Radialis and Extensor Carpi Radialis Longus to control movement. Artificial tendons are fixed to tensioning screws that when rotated exert a constant tension.

Tension values in the tendons are determined via miniature beam load cells which bridge each tendon system (figure 6). Discreet values of tension were applied to each artificial tendon to approximate the digit grip position. The level of tension applied to the artificial tendons was then incrementally altered; in this way the appropriate grip strength loading conditions (recorded previously in grip strength trials) was achieved.

The six-dimensional fingertip output vector for each digit was recorded, as was the load in the lunate, scaphoid, and the radius and ulna. Three wrist postures were examined per test specimen; neutral, maximum flexion and maximum extension.
3. Results and discussion

3.1 Distribution of forces in Radius, Ulna, Scaphoid and lunate

Previous studies have recorded a broad range of values for load transmission through the ulna in respect to the radius. This scatter of values is found to range anywhere between 9%-40% for ulna load transmission [11,12]. In this study, initially six normal specimens are tested. The relative distribution of loads through the radius and ulna are analysed for various wrist postures (graph 1). This analysis reveals that in the neutral position, approximately 32% of the force is transmitted through the ulna, in maximum extension this increases to around 40% of the total load. Significantly when the wrist is in the position of maximum flexion the load sharing distribution along the ulna increases to 47%. In this state the load is approximately shared equally between the radius and ulna.

Analysis of the relative distribution of load through the scaphoid and lunate reveals that the majority of the load is transmitted through the scaphoid (graph 2). The load sharing is most evenly split between the scaphoid and lunate in neutral position where the lunate bears approximately 42% of the load. This reduces to 36% in the position of maximum flexion and reaches a low of approximately 31% in maximum extension. Future work will examine the change in the load bearing characteristics of normal samples detailed here, with the response observed in the bony anatomy of rheumatoid samples.

3.2 Forces generated in artificial tendon system

Tendon loads are generally assessed directly by means of invasive sensors implanted within or attached to these collagenous structures. Typically buckle force transducers are placed around tendons and fingertip force is recorded in conjunction with the force generated in the individual tendon [13]. Inaccuracy occurs determining tendon forces in this manner due to the sensory deprivation that subjects experience, due to anesthesia. Maximum grip strength or fingertip force generation is difficult to achieve in these circumstances. This initial study analyses the forces generated during cadaveric grip strength trails in the two artificial flexor tendons of the index finger; the Flexor Digitorum Profundus (fdp) and Flexor Digitorum Superficialis (fds) (graph 3). It can be seen that the forces in the fds tendon are significantly lower than the in the fdp for the same externally applied grip strength. This phenomenon is most apparent in neutral position where the force in the fdp is approximately 41N as apposed to a tensional force of 94N recorded in the fds. Parity is restored somewhat in the position of maximum extension, however there is still a significant difference between the tension exerted by these flexor tendons. It is noted that there are limitations that must be considered when interpreting the tendon forces obtained here. This artificial tendon system cannot accurately describe the complex mechanism that occurs within the tendon/muscle system in order to produce the desired flexional force at the fingertip. In future work, the forces generated in the complete tendon systems will be analysed in relation to the maximum grip strength produced.
4 Conclusion

This study has revealed fundamental information regarding the load sharing mechanism within the wrist subjected to a complex loading condition. A clearer picture of the way in which load is conveyed through the scaphoid, lunate, radius and ulna during a routine task has been obtained. In addition the range of motion over which this information has been attained has clinical significance. This data will be used in future research to validate a subject-specific FE model simulation with the eventual goal of developing a virtual hand surgery tool.

References


