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MEASUREMENT OF THE GEOMETRY OF THE DISTAL FEMUR USING ROBOTIC 3D ULTRASOUND.

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INTRODUCTION

Currently, Computed Tomography (CT) is the gold standard method of preoperative imaging for guided knee arthroplasty systems, such as the Makoplasty (Roche, O'Loughlin, Kendoff, Musahl, & Pearle, 2009). However, this method is costly (Fred, 2004) and applies a potentially dangerous dose of ionising radiation to the patient (Albert, 2013). Ultrasound imaging has the potential to provide an alternative to CT in this capacity by offering comparable accuracies, while reducing cost and eliminating the risk of ionising radiation. A system was developed which allows for imaging of the bony surface of the distal femur using imaging methods usually found in non-destructive testing (Holmes, Drinkwater, & Wilcox, 2005). This serves to establish a proof of concept for a full 3D knee imaging scheme.

MATERIALS AND METHODS

An artificial human distal femur made from fibre strengthened epoxy (Sawbones, VA, USA) and a bovine distal femur were submerged in a water bath and imaged using a 128 element 5MHz linear probe. The transducer was driven by a Diagnostic Sonar Ltd. (Livingston, Scotland) FlawInspecta phased array driver, which allowed for Full Matrix Capture (FMC). Following a cuboidal path, the probe was manoeuvred around the specimen by a Kuka KR5 Arc HW 6 axis robot. Bespoke probe mounts and calibration parts were manufactured to determine the probe position and orientation relative to the robot's coordinate system. Measurement with a Faro (FL, USA) Quantum touch probe found the parts to be within 0.1mm of the desired dimensions. Using synchronised probe position and ultrasonic data capture, 337 ultrasonic data acquisitions were performed for the human distal femur and 1090 for the bovine distal femur - both using FMC. The data were post-processed using the Total Focussing Method (TFM) and the Synthetic Aperture Focussing Method (SAFT), which provided 2D images. Contour extraction was performed on each image and the resulting points were translated and transformed using the associated positional data, providing 3D point clouds representing the surface. Using Geomagic Studio 12, wrapping algorithms were applied to the point clouds, returning 3D surface models. Both distal femurs were laser scanned using a Faro Quantum, providing accurate reference models for accuracy analysis.

RESULTS

The ultrasound-derived models were of a relatively high level of accuracy, achieving sub-millimetre mean error for both specimens, as shown in Table 1. This was achieved not with TFM, but rather a small aperture variety of SAFT. However, both data sets returned relatively large maximum errors. In the human model, this was presented as a circular feature, as can be seen in Figure 1. The human distal femur featured a drilled hole at this point, the representation of which was present in the point cloud, but was lost due to the wrapping function during 3D model production. The standard deviation was small for the human distal femur, but over 1mm for the bovine distal femur. Large errors in the bovine model corresponded to incomplete regions in the reference model, caused by line of sight issues during laser capture. These gaps likely account for the large standard deviation.

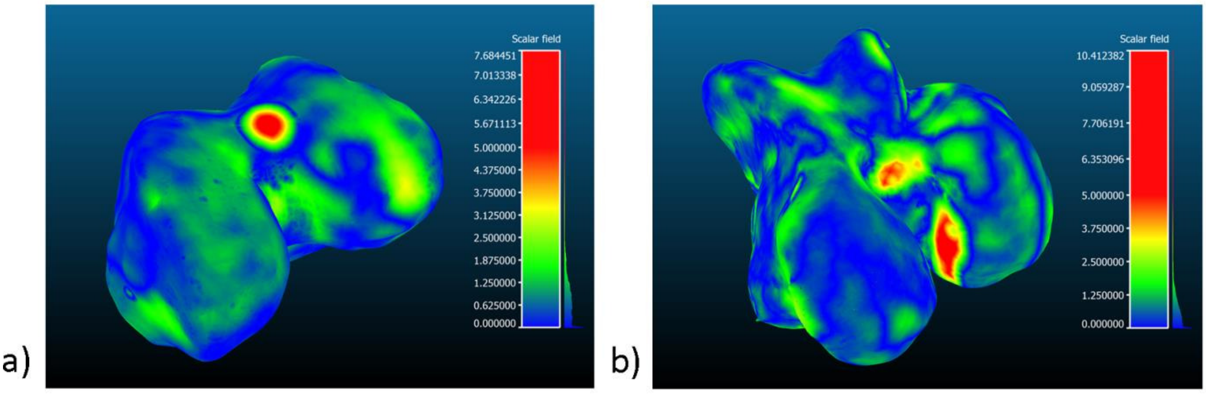

Figure 1: Result of matching resultant 3D models with the reference models. Part (a) shows the composite distal femur comparison, while part (b) displays the bovine distal femur.

	Mean Error (mm)	Maximum Error (mm)	Standard Deviation (mm)
Composite Human Distal Femur	0.8201	7.6845	0.6401
Bovine Distal Femur	0.8797	10.4124	1.0157

Table 1: The results of the comparison between resultant 3D models with the reference models.

DISCUSSION

Robotically controlled ultrasound systems have been employed to image and reconstruct bony surfaces of the femur before, but were intended only for registration of real world position with CT data (Torres, Sanches, Goncalves, & Martins, 2012). Others have employed optically tracked systems that require prior knowledge of the geometry of the bone (Barratt et al., 2008; Krysztoforski, Krowicki, Swiatek-Najwer, Bedzinski, & Keppler, 2011). The presented system, on the other hand, requires no previous information. While a number of biomedical ultrasound research efforts have employed non-commercial ultrasound systems (Jensen, Nikolov, Gammelmark, & Pedersen, 2006), most employ conventional systems, which do not allow for wide ranging imaging strategies (Jensen et al., 2005). The system used herein allows for FMC capture and, as such, provides the ability to test a number of imaging methods post capture. One such method is TFM, which is seen as the gold standard in classical beamforming (Fan, Caleap, Pan, & Drinkwater, 2014). It, along with SAFT, is used heavily in ultrasonic NDT research, but has found little uptake in biomedical imaging. The mean accuracy of the system met the target of 1mm error often reported for CT (Viceconti, Zannoni, Testi, & Cappello, 1999). However, both surface models suffered from high maximum errors and, in the case of the bovine distal femur, a high standard deviation. It is believed that with a more accurate reference model, the standard deviation, maximum error and, to a lesser extent, mean error would be reduced in the bovine distal femur. Additionally, filling of the hole in the human distal femur - an abrupt feature not expected in vivo - would reduce the error associated with the wrapping algorithm's hole filling. Finally, it is believed that improvements to the robot calibration procedure would further reduce errors. Despite the relative success of this study in showing the principle of functionality of the system, the conditions under which the data were recovered were unrealistic. As such, future work will look to incorporate the problem of soft tissue penetration in FMC and issues involving line of sight in intact knee joints.

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DISCLOSURES

None.