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Original Article

Analysis of congruence for talar dome geometry among tali of different sizes

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ABSTRACT

Traumatic injury and idiopathic avascular necrosis of the talus bone can result in osteochondral lesions of the talus leading to pain, motion loss, and disability. Treatment with osteochondral allografting currently requires the donor talus to be size matched to the recipient talus to ensure precise fits. Eliminating or reducing the need for size matching would lessen costs and the delay between diagnosis and treatment. 3D models of 12 tali of varying sizes were used to analyze curvatures and profiles of select areas on the talar dome. The allograft procedure was mimicked to compare the results between using 20 mm and 30 mm osteochondral allografts with, and without, donor size matching. The observed curvatures and profiles on the talar dome were found to be consistent between tali of different sizes. Size matching was not required to have acceptable levels of deviation between donor and recipient tali when using 20 mm length segments. Deviations without size matching were found to be very similar to the deviations with size matching with only 14.8% of the fits without size matching having larger deviations (although less than 1.5 mm) than those with size matching. Using the 30 mm segments, there was a significant difference between the small female tali and the largest male tali. Thus, donor size matching is not necessary when treating large osteochondral lesions of the talus with an osteochondral allograft taken from the central 20 mm of the donor talar dome, and only sex matching may be necessary for 30 mm grafts.

1. Introduction

Traumatic injury or idiopathic avascular necrosis of the talus bone often results in the collapse of the subchondral bone and cartilage, termed an osteochondral lesion of the talus (OCLT) [1]. Because the ankle joint is highly congruent, pain, dysfunction, and loss of motion can occur [2]. Reconstruction of these lesions larger than 1 cm in diameter often requires osteochondral allografting [3]. This procedure has the benefit of preserving joint congruency and allowing anatomy restoration irrespective of the defect's width, depth, or shape [1,4].

Currently, tissue availability is limited, expensive, and restricted by the need for size matching. Size matching increases the waiting period to receive surgical treatment due to the logistics of obtaining appropriate imaging, ordering the talus, waiting for an appropriate sized donor, and the very limited availability of companies that provide this service; thereby prolonging the patient's disability [1]. Therefore, elimination (or reduction) of size matching would increase tissue availability as donor talus bones could be harvested on an “as needed” basis by smaller tissue recovery centres. This will reduce the amount of resources required, allowing smaller scale tissue banks to participate, further saving money and time as local tissue banks could be used.

Trovato et al. analyzed the 3D geometry of 50 male tali and 41 female tali to support the development of a generic template for an implantable talar prosthetic [2]. This resulted in a generalization of the complex talus bone geometry and a conclusion that all intact human tali have the same shape and that talar domes are scales of each other (same shape but not necessarily same dimensions). Our hypothesis is that the central 20 mm of the talar dome could be interchangeable between patients with different sized tali due to the flatness of the talar dome and similarity of talar dome shapes. Extending from that, an allograft from the central 20 mm of a cadaver donor's talar dome could be transplanted to a patient with a different sized talus with a less than 1 mm step deformity. The 1 mm step deformity was selected based primarily on the basic orthopaedic intra-articular fracture reduction principles of less than 2 mm step deformity within a joint and the lack of consensus in the literature on what constitutes a significant step

Abbreviations: OCLT, osteochondral lesions of the talus; FS, smallest female tali; MS, smallest male tali; MM, average male tali; ML, largest male tali; NURBS, non-uniform rational basis splines; CCM, curvature colour map; AP, anteroposterior; ML, mediolateral; DCM, deviation colour map; RMS error, root mean square error of all points in comparison

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deformity. For example, 1 mm is the amount of talar shift that greatly reduces tibiotalar contact area [5,6] but a 1 mm shift has been shown to result in acceptable post osteochondral plug transplantation in a sheep model [7]). In this study, talar dome curvature and profile shape are analyzed and compared between different sized tali. The osteochondral allograft procedure is also mimicked in a reverse engineering software package to find the best, average, and worst graft fits possible.

2. Methods

3D model data from DICOM CT scans of intact, male (50 tali of age 32.1 ± 15.4 years) and female (41 tali of age 43.5 ± 14.7 years) talus bones were acquired from Trovato et al. [2]. Ethical approval was obtained from the University of Alberta ethical review board. CT scans were imported into the image processing software MIMICS (Materialise NV, Belgium) for creation of masks that would cover the talus bones. These masks were used to create 3D models acquired for this study.

In order to compare *extreme* differences amongst obtained talus bones, 12 tali (volume 39341 ± 18427 mm^3) were chosen and assembled into four different volume groups (n = 3). The tali were organized into four group: female very small (FS), male small (MS), male medium (MM), and male large tali groups (ML), with their volumes detailed in Table 1. The three FS tali consisted of the smallest volumes from the 41 available and were notably smaller than the MS tali. The MS, MM, and ML tali groups were populated with models from the 50 male tali available with volumes closest to the: minimum male talus volume, average male talus volume, and maximum male talus volume, respectively. The models constituted STL files with triangulated meshes composed of a large number of elements ranging from 20,000 to 60,000 depending on the size of the talus. The solid models were imported into Geomagic Studio 2014 (Geomagic®, Morrisville, North Carolina; USA) for model orientation and alignment.

The orientation process for all analyses was as follows: import models into Geomagic Studio, scale tali to the volume of talus bone ML1 (largest talus bone), align the tali to ML1 using the best fit alignment function built into Geomagic Studio, and scale the tali back to original volumes. This alignment provided all tali the same orientation for profile curve and graft creation. Since intact, human talus bones show a high degree of bilateral symmetry [8], all tali were configured to show as right tali. The last step in the alignment was to rotate each model so the highest points on the medial and lateral shoulders were level with each other for reproducibility. Fig. 1 shows the final orientation of a sample talus (with bounding box), along with the anatomical directions used in this study.

For talar dome curvature analysis, the 12 models were exported to Geomagic Design X 2016 (Geomagic®, Morrisville, North Carolina; USA) after alignment. Talar domes of each model were isolated using the built-in split function allowing removal of portions of the 3D model. The quality of each mesh was improved using functions built into Geomagic Design X (such as re-mesh, decimate, optimize mesh, and small amounts of smoothing) to prepare for the creation of an analytical surface.

Table 1
Individual tali and their corresponding size groups.

Volume group	Group average volume [mm^3]	Subject talus	Talus bone volume [mm^3]
Female	23167	FS1	20915
		FS2	23083
		FS3	25505
Small	34163	MS1	34566
		MS2	31825
		MS3	36100
Medium	44254	MM1	43849
		MM2	43386
		MM3	45527
Large	53136	ML1	57768
		ML2	50992
		ML3	50650

The built-in mechanical autosurfacing function in Geomagic Design X was utilized to create the analytical surfaces needed. This option in the software automatically creates non-uniform rational basis spline "NURBS" surfaces by constructing a 3D patch network on the entire mesh of the model and then creating continuous NURBS surfaces by fitting control points in the network (Geomagic®, Morrisville, North Carolina; USA). After the models were converted to analytical surfaces, the Geomagic Design X feature Accuracy Analyzer TM was used to create two different sets of curvature colour maps (CCM's) for all 12 tali, showing both maximum and minimum surface curvature values. Maximum CCM's display the estimated maximum principal curvature value [9], either positive or negative, at that particular point on the surface. Conversely, minimum CCM's display the minimum estimated principal curvature value [9] at that point on the surface (either positive or negative). The maximum and minimum CCM's were plotted together for visual appraisal.

Subsequently, a preliminary analysis of talar dome geometry was done by extracting profile curves at certain anatomical landmarks to determine whether certain sections of the talar dome were similar enough to allow for donor selection without size matching. Talar domes of all 12 tali were isolated, after alignment, in Geomagic Studio 2014 using the built-in polygon trim function. The trim plane was placed where the cartilage was estimated to end which was approximately 30% of the talar height down from the highest point (top of the bounding box). Fig. 2 shows the location of the trimming plane for talus ML1. Isolated talar domes were then converted to non-uniform rational basis spline (NURBS) surfaces using the organic autosurfacing function in Geomagic Studio to preserve as much surface detail as possible.

Four profile curves were taken on the talar dome using Geomagic Studio's "Create Curves by Section" function. This function creates a 2D outline of a 3D object where that object intersects a specified plane. Three curves were in the anteroposterior (AP) direction (medial shoulder, lateral shoulder, and middle) and one was in the mediolateral (ML) direction (Fig. 3). The medial and lateral AP curves were captured at the highest point such that the curves approximated the line of high maximum curvature found during the curvature analysis along the lateral and medial shoulders. The middle AP curve was determined by splitting the distance between the other two AP planes. The ML curve was taken along the line connecting the highest points on the medial and lateral shoulders of the talar dome.

The grafts investigated in this study were 20 (or 30) mm in the AP direction (length), 15 mm in the superior-inferior direction, and 15 mm in the medial-lateral direction (Fig. 1). This required the talar dome of the donor model to be cut in Geomagic Studio such that the simulated graft matched these dimensions.

For graft creation, tali were aligned as before to ensure the same orientation, and Geomagic Studio's trim by plane function was used to separate the required graft area (15 × 15 × 20 mm or 15 × 15 × 30 mm) from the rest of the talus. The centre of the graft was determined to be equidistant from the estimated anterior and posterior natural cartilage edges on either the lateral or medial shoulder. The talus was cut at equal distances from the central point on both sides (approximately perpendicular into the talus) to get the desired graft length. The graft was further separated by cutting 15 mm down from the top edge of the individual model's bounding box. The separation was completed by trimming the model approximately 15 mm towards the centre in the mediolateral direction. After the grafts were made, both the grafts and the tali were organically autosurfaced. Table 2 shows the four different sets of analysis combinations that were done with these grafts, and which tali were included.

Geomagic Studio's best fit align function was used to align each graft to a complete talus model. This allowed for the creation of deviation colour maps (DCM's) for each graft fitting, which show locations

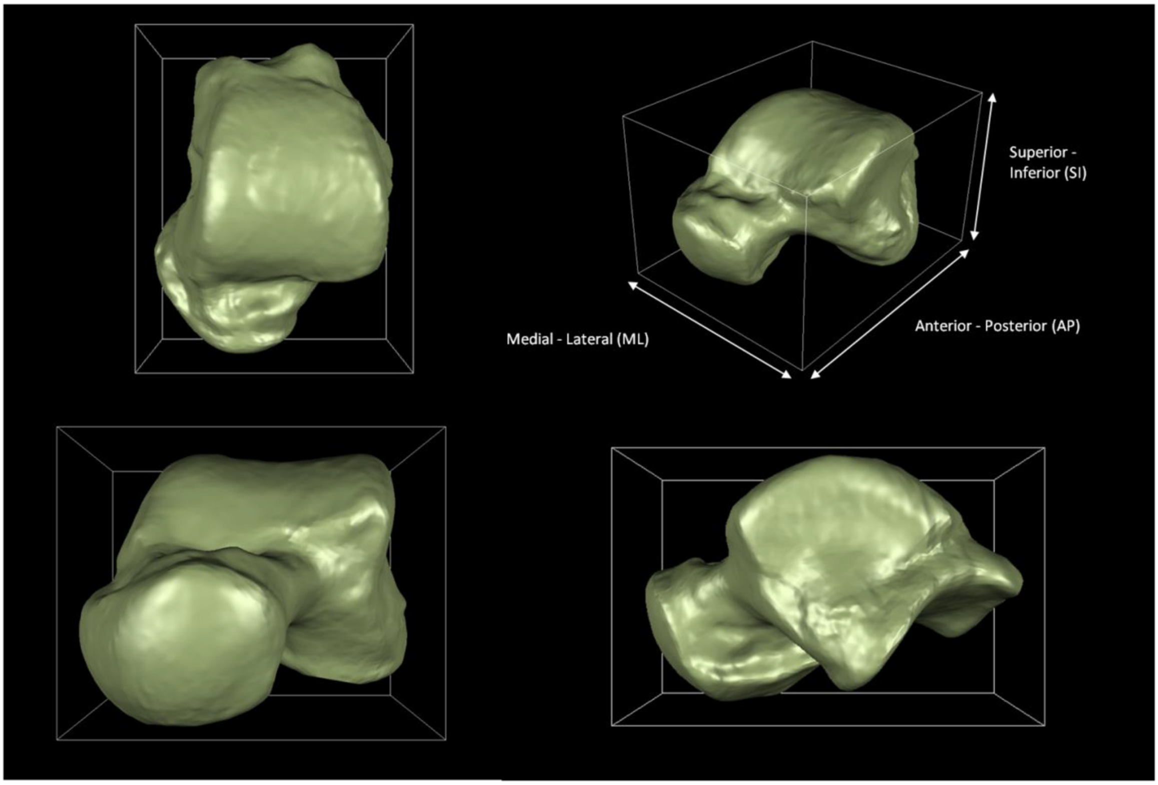

Fig. 1. Orientation of the tali (including bounding box).

of deviations on the graft surface. The graft was deemed to be acceptable when the distances between corresponding points on the surfaces of the talus and the graft were less than 1 mm [5,6].

To recreate current surgical practice, DCM's were created between tali from the same size groups (large graft to large talus, medium graft to medium talus, etc.). Analysis group 1 represents our proposed method where size matching is not used while Analysis group 2 represents current practice. DCM's for these two groups were compared to determine how similar our proposed practice is compared to current practice.

Because all tali have a similar shape [2], variations due to scale only were investigated by scaling the largest talus (ML1) to the average volumes of the four size groups (FS, MS, MM, and ML) as shown in Table 3. This prevented small variations in shape (from mesh creation error, slightly abnormal tali, etc.) from affecting the deviations when a graft was best fit to a talus bone (Analysis group 3).

Some surgical cases have larger OCLs that necessitate larger grafts. This was investigated in the same way using 15 × 15 × 30 mm dimensions, with the only exceptions being: talus ML1 was only scaled to the ML, MS, and FS group average volumes (to show extremes within the male tali and between the male and female tali), and the graft was made to be 30 mm in length, instead of 20 mm (Analysis group 4).

3. Results

Visual inspection of the curvatures on the talar dome allowed for initial insight into the variation of curvature on talar domes belonging to tali of various sizes. The maximum curvature values along both shoulders of the talar domes were greater than 0.25 mm^{-1} for all subject talus bones considered. The minimum curvature values in the same areas were predominantly between 0 and 0.075 mm^{-1}. The central portions of all talar domes had large areas with maximum curvature values between 0 and 0.075 mm^{-1}. All talar domes also had small sections with maximum curvatures between −0.05 and 0 mm^{-1}

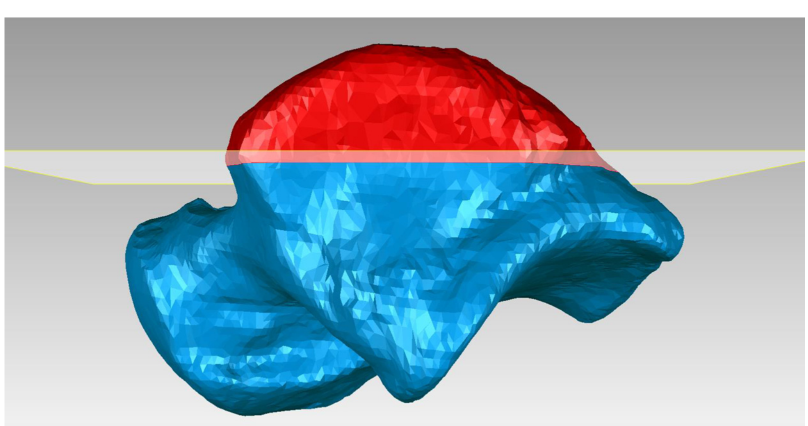

Fig. 2. Location of the trimming plane on talus ML1.

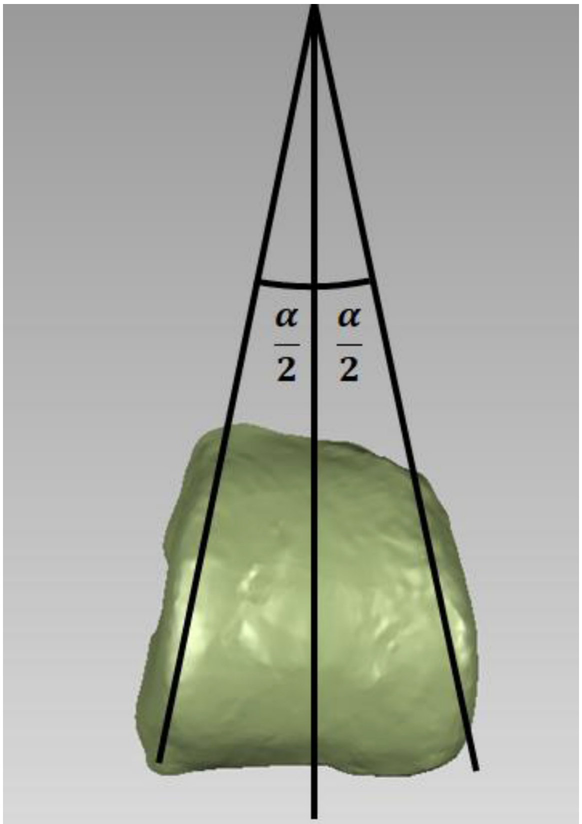

Fig. 3. Top down view of talar dome showing how the middle AP curve was found.

running down the very centre. The minimum curvature values in this central portion varied between -0.025 and 0.025 mm^{-1}. Fig. 4 shows CCM's for maximum and minimum curvatures, while Table 4 summarizes these curvature values at different anatomical locations as determined by visual inspection.

The extracted profiles had average curvatures (estimated by Geomagic Studio) as shown in Table 5. The 12 lateral, medial, middle, and mediolateral (ML) profiles had average curvatures (found by averaging the profile curvatures of each subject for a particular profile) of 0.128, 0.083, 0.076, and 0.118 mm^{-1} respectively.

The best, average, and worst graft fits for the proposed procedure in Analysis group 1 (comparing all tali except MM) were chosen based on their estimated RMS error (root mean square error of all points in comparison) during the best fit alignment procedure. When comparing the 9 tali to each other, the best, average and worst fits for the lateral shoulder are summarized in Table 6 along with their corresponding RMS errors and what percent of the graft surface was outside the accepted range (± 1 mm).

For Analysis group 2 (grafting between tali of the same size group), the best, average and worst fits on the lateral shoulder are shown in

Table 3
Average volumes of the talus size groups and the corresponding volume scale value for talus ML1.

Size group and corresponding denotation	Average volume of group [mm^3]	Scale value for talus ML1
Female (Female-ML1)	23167	0.737
Small (Small-ML1)	34163	0.839
Medium (Medium-ML1)	44254	0.915
Large (Large-ML1)	53136	0.973

Table 7, which summarizes these fits along with their corresponding RMS errors and what percent of the graft area had unacceptable deviation (outside ± 1 mm). Figs. 5 and 6 show DCM's of the 12 fits from Tables 6 and 7.

The percentage of graft surface area that had deviations beyond ± 1 mm was plotted against the corresponding RMS errors to identify trends (Fig. 7). A parabolic relationship between RMS error and percentage of the graft surface with deviations outside of ± 1 mm were found, showing that increasing RMS errors correspond with increasing area with unacceptable deviation.

The percentage of surface area with deviation greater than ± 1 mm was also plotted against the volume ratio (volume of larger talus/volume of smaller talus) for each graft fitting to determine if there was a relationship between them. No trends were found.

When talus ML1 was scaled to different volumes (Analysis group 3) and best fit aligned, the worst fit (fit with the highest RMS error of 0.34 mm) was found to be the female-ML1 lateral graft best fit to the large-ML1. The DCM's for this fit and the worst fit on the medial side (female-ML1 graft best fit to the large-ML1, with an RMS error of 0.31 mm) are shown in Fig. 8. Visual appraisal concluded that the rest of the graft fits, including all the combinations performed had acceptable levels of deviation.

The RMS errors for Analysis group 3 were also plotted against the volume ratio to determine any potential trends. There was a linear relationship that indicated the RMS error of the best fit alignment would increase with the volume difference between two volume scales of talus ML1. The percentage of the surface outside of ± 1 mm as a function of volume ratio was not considered since all the tali had acceptable deviations (within ± 1 mm).

When the graft was expanded from 20 mm to 30 mm in the AP direction (Analysis group 4), the worst fits as determined by RMS errors were the female-ML1 lateral graft fit to the large-ML1, and the female-ML1 medial graft fit to the large-ML1. When compared to the same fits for the 20 mm graft, the RMS error for the lateral and medial fits increased from 0.34 to 0.69 mm and from 0.31 to 0.65 mm, respectively. Both fits showed deviations outside of ± 1 mm on the edges of the transplant as shown on their DCM's (Fig. 9).

To see if the deviation levels could be improved, the deviations for a 30 mm graft between the large-ML1 and small-ML1 tali were investigated. The worst fit on the lateral side between these two volume scales was the small-ML1 graft fit to the large-ML1 (RMS error of 0.39 mm). The worst fit on the medial side was the large-ML1 graft fit

Table 2
Sets of analysis combinations performed on graft fittings.

Analysis group	Description	Talus	Graft
1	20 mm graft fitting between tali of different individuals	9 tali – FS, MS and ML groups (excludes MM group) (from different size groups)	9 tali – FS, MS and ML groups (excludes MM group) Compare tali from different size groups
2	20 mm graft fitting between tali of different individuals	All 12 Tali	Compare with tali from the same size group
3	20 mm graft fitting between volume scales of the same talus	Scales of ML1	Compare different scales of ML1
4	30 mm graft fitting between volume scales of the same talus	Scales of ML1	Compare different scales of ML1

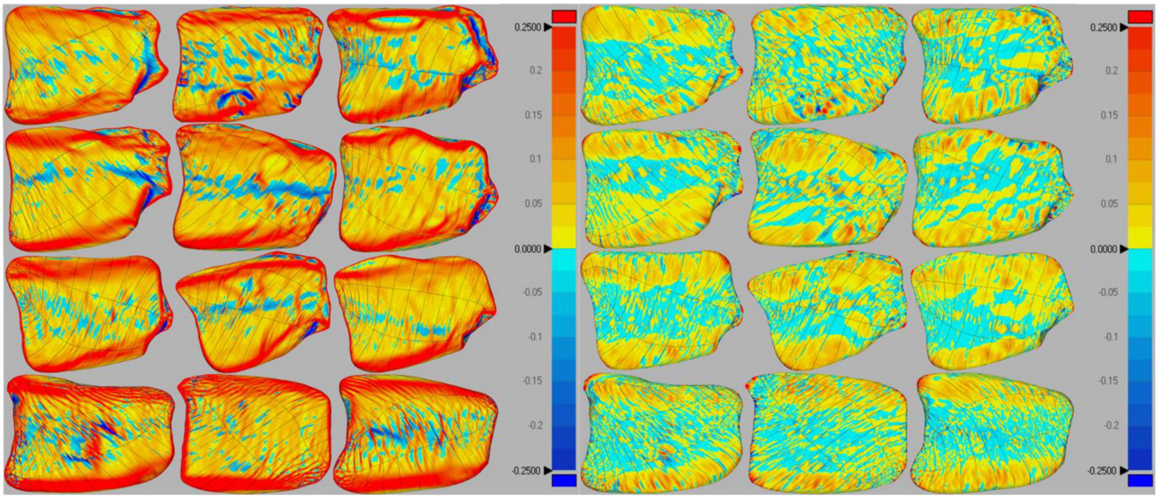

Fig. 4. CCM's showing maximum curvature values (left) and minimum curvature values (right) on the talar domes of 12 subjects. Rows from top to bottom: ML, MM, MS, FS tali. Columns from left to right are the three different tali from each group. Note: scale in units of mm^{-1}.

Table 4
Curvature values (maximum and minimum) at different locations on the talar dome (determined through visual inspection).

Location on talar dome	Maximum curvature values [mm^{-1}]	Minimum curvature values [mm^{-1}]
Medial shoulder	Greater than 0.25	Between 0 and 0.075
Central area	Between 0 and 0.075	Between −0.025 and 0.025 (≈ 0)
Lateral shoulder	Greater than 0.25	Between 0 and 0.075

to the small-ML1 (RMS error of 0.33 mm). The lateral fit had a small area of notable negative deviation.

4. Discussion

Currently, size matching is required when selecting cadaveric donors for osteochondral allografts when treating large OCL's that have failed initial conservative management and first-line surgical procedures. Elimination or reduction of size matching would benefit the patient by increasing tissue availability, minimizing surgical delays, and reducing costs. We hypothesized that osteochondral allografting of talar dome lesions 20 mm or less in length could be performed without size matching.

Results from our curvature analysis supported that curvatures in nearly every area of the talar dome are maintained across many different sized tali, which supported our hypothesis. In particular, the maximum curvature values on the medial and lateral shoulders did not vary much between different sized tali. This, combined with the fact that the central areas along the medial and lateral shoulders are essentially flat, supported our hypothesis that an allograft utilizing this portion would be successful between patients with different sized tali.

To investigate whether our proposed practice of non-size matching is appropriate, three scenarios were examined using the best, average, and worst graft fits were found based on their RMS errors during best fit alignment for several situations. The first scenario investigated was allografting between tali belonging to different volume groups (FS, MS, and ML) and comparing that to the current practice of grafting between tali from the same volume group (i.e. size matched) (Figs. 5 and 6). The MM group of tali was excluded (when comparing tali from different volume groups) because all the other volume groups considered had greater size differences among the groups. For example, when MM was compared to each group individually, the differences were smaller than when ML was compared to each group. Once this set of comparisons was complete, a second scenario of simulated grafts was completed considering the deviations caused only by scale, not shape. This was indicated because it gave insight into what obtainable results of allografting procedures if talus *shape* was guaranteed to be exact between donor and recipient. In the third scenario, 30 mm allografts were mimicked only considering deviations due to scale. The ML scale talus was compared to the FS scale talus first (Fig. 9). After observing areas with deviations outside ± 1 mm, the ML scale talus was also compared to the MS scale talus to see if only sex (not size) had to be considered when matching a donor and recipient.

Both the best and average graft fits between tali from different size groups (ML, MS, and FS) showed acceptable levels of deviation (within ± 1 mm) with minimal difference to current size matching clinical practice as determined by DCMs and RMS errors. When the worst fits were determined between the different sized tali, there were areas with deviations higher than what may be considered acceptable, but these were still within ± 1.5 mm (Figs. 5 and 6). Interestingly,

Table 5
Curvatures for the extracted talar dome profile curves as estimated by Geomagic Studio 2014 (Geomagic®, Morrisville, North Carolina; USA).

Size group	Profile average curvature [mm^{-1}] ± standard deviation			
	Lateral profile	Medial profile	Middle profile	ML profile
Large	0.123 ± 0.006	0.081 ± 0.024	0.074 ± 0.010	0.126 ± 0.033
Medium	0.106 ± 0.012	0.069 ± 0.008	0.060 ± 0.007	0.098 ± 0.008
Small	0.113 ± 0.018	0.069 ± 0.012	0.075 ± 0.019	0.106 ± 0.015
Female	0.170 ± 0.042	0.113 ± 0.009	0.095 ± 0.008	0.141 ± 0.034

Table 6
Best, average, and worst fits on the lateral and medial shoulders between tali belonging to 3 different volume groups.

		Fit	Volume groups	RMS error [mm]	Percent outside of ± 1 mm [%]
Lateral shoulder	Best	MS3 graft fit to ML2	MS fit to ML	0.19	0
	Average	MS2 graft fit to FS2	MS fit to FS	0.33	0.2
	Worst	FS1 graft fit to MS1	FS fit to MS	0.76	12.3
Medial shoulder	Best	MS1 graft fit to ML2	MS fit to ML	0.23	0
	Average	ML3 graft fit to FS3	ML fit to FS	0.47	1.3
	Worst	ML3 graft fit to MS3	ML fit to MS	0.90	33.6

Table 7
Best, average, and worst fits on the lateral and medial shoulders between tali belonging to the same volume group.

		Fit	Volume group	RMS error [mm]	Percent outside of ± 1 mm [%]
Lateral shoulder	Best	MM1 fit to MM3	MM	0.14	0
	Average	ML2 fit to ML3	ML	0.32	2.0
	Worst	FS1 fit to FS2	FS	0.57	4.9
Medial shoulder	Best	MS2 fit to MS1	MS	0.29	0.2
	Average	FS3 fit to FS2	FS	0.44	3.6
	Worst	MS3 fit to MS1	MS	0.63	10.8

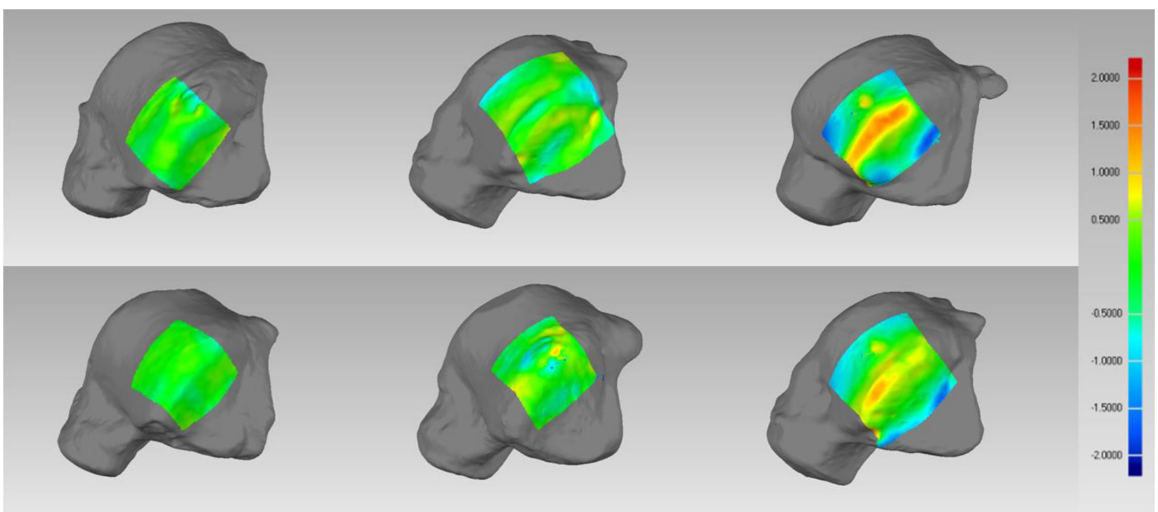

Fig. 5. DCM's of the lateral fits between tali from different volume groups (top row) and tali from the same volume group (bottom row). From left to right, the fits are: the best fit, the average fit, and the worst fit. Top row (left to right): MS3 graft to ML2, MS2 graft to FS2, and FS1 graft to MS1. Bottom row (left to right): MM1 graft to MM3, ML2 graft to ML3, and FS1 graft to FS2. Note: scale in units of mm.

current practice was only marginally better than our proposed practice in the worst-case scenario meaning that even with precisely size matched tali, there are areas of unacceptable deviation. In this study, only 10 of the 54 fits (18.5 %) on the lateral side and 6 of the 54 fits (11.1 %) on the medial side (between tali from different volume groups) had RMS errors greater than the corresponding worst fits from the current practice. This showed that only a small portion of the outcomes from our proposed practice would be worse than what is currently done and, in these cases, the deviations were less than 1.5 mm. It is important to note that the talus groups chosen were the extremes of the tali available, making it even less likely to have unacceptable incongruity. This was confirmed when fits were investigated using only one talus to minimize possible errors (due to mesh creation error, abnormal tali, etc.) (Fig. 8).

The results of a 30 mm graft (using one scaled talus) were investigated to lay the groundwork for future studies involving larger allografts. When the FS scale talus was compared to the ML scale talus, there were unacceptable deviations (the vast majority of the deviations were still under 2 mm) and the RMS errors were similar to the worst-case scenarios when best fitting 20 mm grafts between different sized tali belonging to different individuals (Fig. 9). When the MS scale talus was compared to the ML scale talus, the deviations found were acceptable. The RMS errors for these fits were also close to the average fits for the 20 mm grafts between different sized tali belonging to separate individuals. The fact that the male comparisons had acceptable deviations (while the FS scale compared to the ML scale did not), and the fact that all tali are the same shape [2], suggested that only sex matching (and not size matching) is necessary for large 30 mm grafts. However, most female tali do not have the extremely small volumes used in this study as we used the smallest 3 tali out of the 41 available, so it is likely that the typical female talus would show similar levels of deviation as the small male talus when compared to larger tali. This also needs to be investigated further.

The selection of 1 mm being an acceptable deviation was determined based on accepted fracture reduction principles. Some animal studies support this, but it is not a well-defined benchmark. Huang et al. demonstrated that a 1 mm countersunk osteochondral plug in a sheep model six weeks post transplantation resulted in good macroscopic joint restoration and reasonably good microscopic restoration while a 2 mm countersunk plug essentially failed [7]. Fansa et al. performed a fresh frozen cadaveric study using knee osteochondral plugs into the medial talus and demonstrated that a plug 0.4 mm proud (their largest

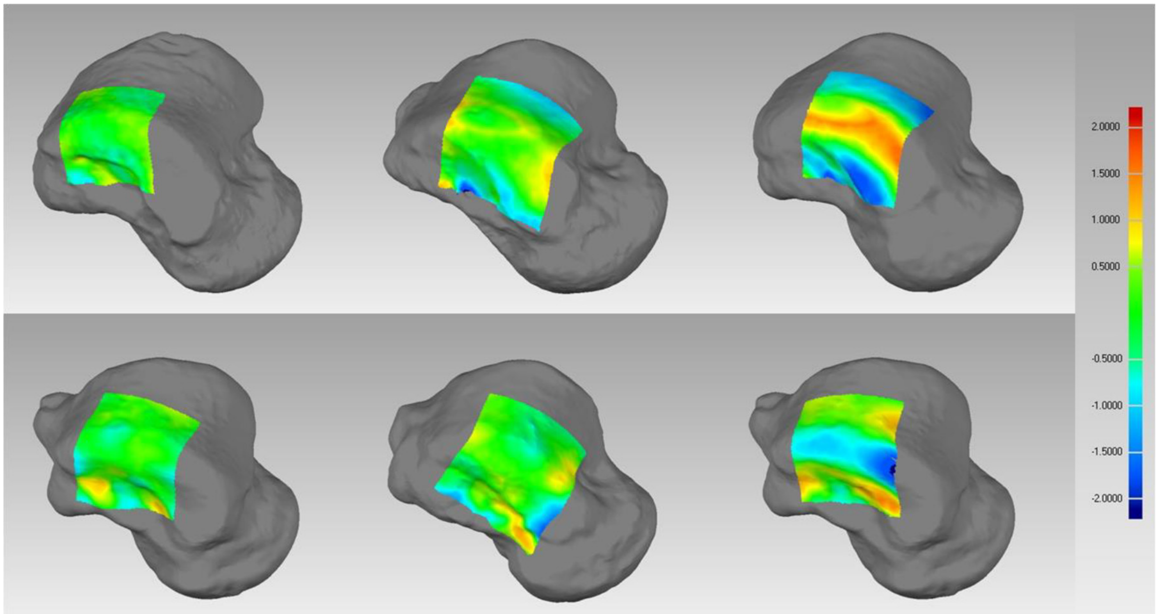

Fig. 6. DCM's of the medial fits between tali from different volume groups (top row) and tali from the same volume group (bottom row). From left to right, the fits are: the best fit, the average fit, and the worst fit. Top row (left to right): MS1 graft to ML2, ML3 graft to FS3, and ML3 graft to MS3. Bottom row (left to right): MS2 graft to MS1, FS3 graft to FS2, and MS3 graft to MS1. Note: scale in units of mm.

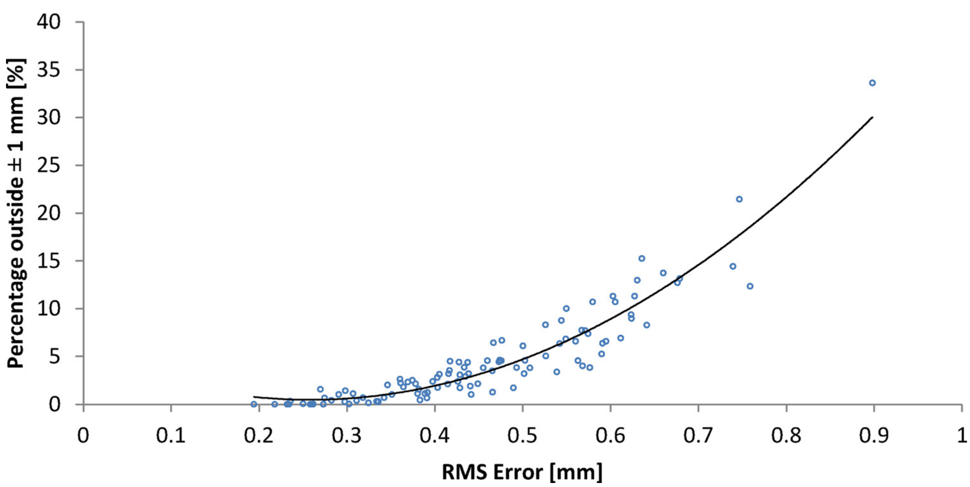

Fig. 7. Percent of graft surface with deviations outside of ± 1 mm as a function of RMS error (from Analysis group 1).

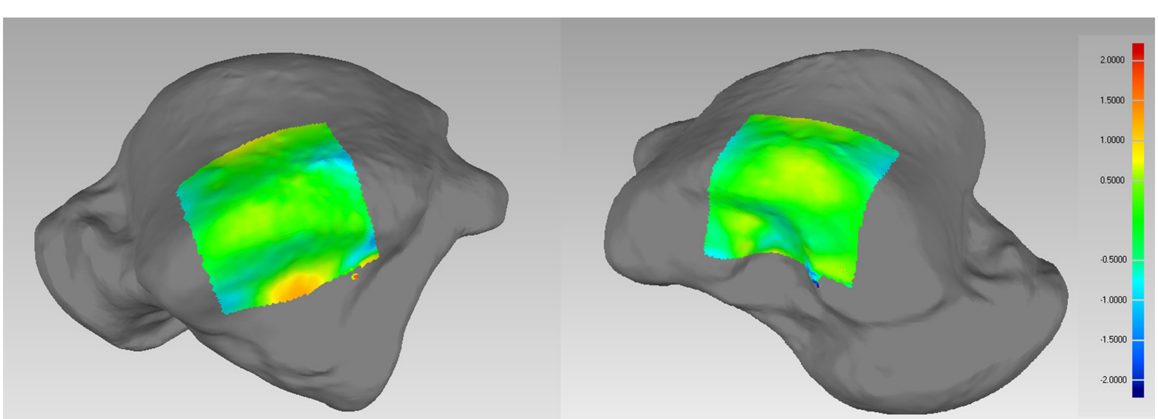

Fig. 8. Worst fits on the lateral (left) and medial (right) shoulders of talus ML1 scaled to different volumes. The fits are female-ML1 lateral graft fit to large-ML1 (left) and female-ML1 medial graft fit to large-ML1 (right). Note: scale in units of mm.

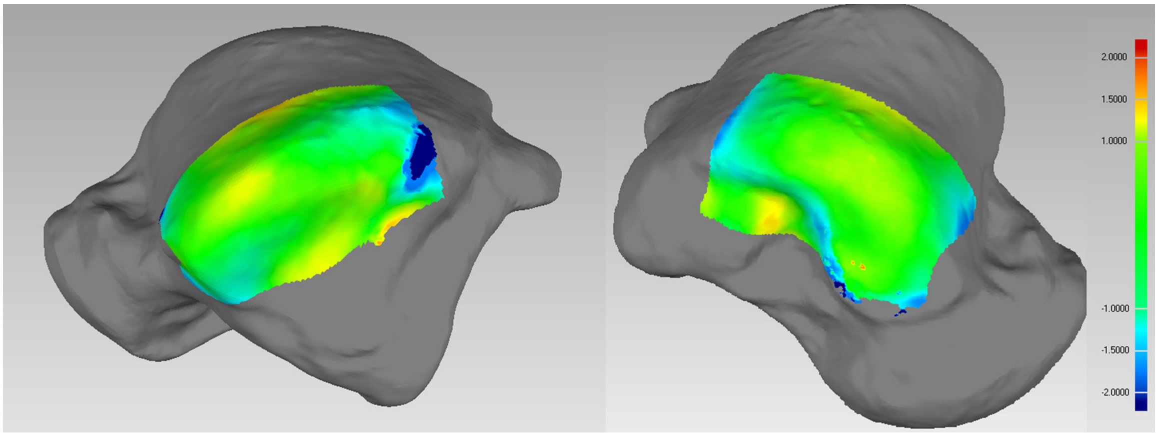

Fig. 9. DCM's for talus ML1's FS lateral (left) and medial (right) 30 mm grafts best fit to the large-ML1 talus. Note: scale in units of mm.

deviation) did not experience increased pressure with loading [10]. Conversely, Koh et al. in a pig knee joint model showed 57% and 48% increase in pressure with osteochondral plugs 1.0 mm and 0.5 mm proud, respectively and 8% and 11% increase in pressure with osteochondral plugs 0.5 mm and 1.0 mm countersunk respectively [11]. To complicate matters further, Wu et al. demonstrated using finite element analysis that even perfect placement of an osteochondral graft can result in contact stress profile changes in the articular surface [12]. Thus, there is no consensus as to what an acceptable deviation is, but it would appear that countersunk grafts are more forgiving than proud grafts. To account for this lack of consensus on what is an acceptable displacement, this study compared a non-matching system with the current "standard of care" size matching system and did not find a large percentage of the data points differed between the two methods, suggesting that size matching is not required. This could improve clinical outcomes by improving access to tissues more rapidly (not having to wait for the exact talus size match), thereby preventing further joint deterioration as a defect does result in altered joint pressures [10,11].

5. Summary and conclusions

Based on the results from this study, it can be concluded that 20 mm osteochondral allografts on the talar dome between individuals with different sized tali typically have acceptable levels (± 1 mm) of deviation. When the worst fits are investigated, they are generally similar to the worst results from the current method of donor selection (with size matching). Considering that only a small amount (14.8%) of the worst cases generated by our method exceeded the severity of the worst cases simulated from current practice, and these deviations were less than 1.5 mm, the proposed method produced results similar to current practice. Preliminary research into 30 mm allografts suggested that only sex matching may be required (not size matching) due to the smaller volumes seen with the smallest female tali for 30 mm grafts. Further work may be done to investigate this.

Declarations of interest

None.

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