

# Changes in shape of the Standardbred distal phalanx and hoof capsule in response to exercise

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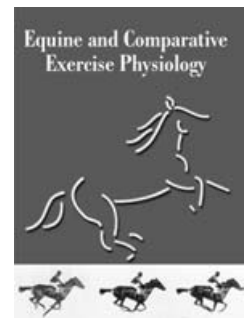
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## Abstract

The aims of this study were to determine whether the equine distal phalanx changes in shape in response to exercise and to relate any osseous changes to those in the hoof capsule. Eighteen mature Standardbred horses were randomly divided into exercise and control groups. Exercised horses were jogged on a straight track at individual mean speeds between 4 and 8 m s<sup>-1</sup> for 10–45 min, 4 days per week for 16 weeks. Both groups were similarly shod and pastured on the same field. Before and after the training period, each horse had digital photographs and magnetic resonance images (MRI) made of the right forehoof. Five linear measurements of the distal phalanx were recorded from the MRI and 24 measurements of the hoof capsule were made on the digital photographs. Small but significant changes in bone width ( $P = 0.039$ ) were found in the controls and in two sagittal measurements of bone length ( $P = 0.039, 0.001$ , respectively) for the exercise group. These changes were slight and did not correlate with changes in shape of the hoof capsule, suggesting that the bone acts as a stable platform for supporting the capsule and withstanding loads.

**Keywords:** horse; distal phalanx; hoof; exercise

## Introduction

Over time, the equine hoof capsule responds to the loads applied during repeated footfalls by actively changing its shape<sup>1,2</sup>. Other factors, such as trimming techniques, gait and direction of travel also affect hoof capsule shape<sup>2,3</sup>. Active change in morphology alters the distribution of stress and strain within the hoof<sup>4,5</sup>, which may in turn stimulate further shape change in a feedback mechanism<sup>6,7</sup>.

Although the effects of mechanical loads on the hoof capsule are starting to be documented, little research has been conducted on exercise-induced shape change of the central core of the horse's hoof, the distal phalanx. The biological response of bone to mechanical loading is an important adaptation to

training<sup>8,9</sup>, which begs the question: does the distal phalanx change in shape with variations in loading regime, or does it remain as a stable platform for the capsule?

The distal phalanx has been investigated from a clinical perspective<sup>10,11</sup> and there are few studies of the normal bone<sup>12,13</sup>. Linford *et al.*<sup>12</sup> examined the normal distal phalanx in racing Thoroughbreds using radiographs. Bone deposition was found in 36 out of 41 horses in their study. These results suggest that, with exercise, the shape of the distal phalanx changes due to an increase in bone formation. However, the primary goal of the study was not to examine morphology in response to exercise, but to determine its normal radiographic appearance. To our knowledge,

there have been no experimental studies conducted investigating specific changes in morphology of the equine distal phalanx in response to variation in loading regime. Bone stress and strain in horses and its effects on remodelling and gross shape of bones has been investigated primarily for the third metacarpal<sup>8,9,14-19</sup>. Most found an increase in dorsal thickness of the bone with exercise, in time frames as short as 7 weeks<sup>8,9,16,17</sup>, while others found no measurable change<sup>18,19</sup>. Taken as a whole, these studies suggest the possibility of changes in shape of the distal phalanx with exercise.

The aims of the present experiment were to examine the responses of the hoof capsule and distal phalanx to a period of exercise, to determine whether each structure changed in shape and whether they changed in concert. Specific objectives were (1) to measure and compare the shapes of hoof capsule and distal phalanx in samples of exercised and unexercised Standardbred horses before and after a 4-month period of exercise and (2) to test for the pairwise correlations among changes in phalangeal and capsular measurements over the experimental period.

## Materials and methods

### Horses

Eighteen mature adult Standardbred horses (12 geldings and six mares) with an average age of 5 years were used. The study was limited to a single breed of horse to eliminate interbreed variability. All horses were of a mature age in order to eliminate any early growth factors of the hoof. Horses were randomly assigned to two groups: control ( $n = 9$ ; six mares and three geldings) and exercise ( $n = 9$ ; nine geldings). During the study, all horses were housed outdoors in the same paddock (200 m<sup>2</sup>). Horses had free-range access to grass and were also given hay when grass was sparse. Horses were kept at a steady weight throughout the project. All horses in the exercise group were given *c.* 1 lb of ration (12% protein horse ration pellets, Floradale Feedmill Ltd., Floradale, ON, Canada) each day in order to compensate for excess calories lost due to exercise. To maintain a steady weight in all horses, the ration was also fed to some control group horses. It contained no hoof-growth promoters (e.g. biotin or methionine) and no additional supplements were given. All horses were shod (on all four feet) and were maintained on a trimming and resetting schedule every 6 weeks, with a number of measures being taken to minimize potential confounding effects of this necessary intervention (these effects will be addressed in the discussion). The same farrier was used throughout and was not told which horses had been allocated to exercise or control groups. He applied the same trimming

principles rigorously to each horse on each visit and did not conduct any correctional trimming or resetting techniques that would significantly alter the hoof's external shape, other than wall length and sole thickness. Every horse was shod with new flat, iron shoes of the same type at the commencement of the experiment, and worn shoes were replaced subsequently as necessary.

The exercise group underwent a 16-week progressive training programme. Horses were jogged at individual mean speeds ranging from 4 to 8 m s<sup>-1</sup>, each horse being allowed to run at its own preferred speed on a given day. They were exercised on a 700 m straight track made of crushed limestone and gravel base, which is representative of a typical harness racing track. Two jog carts were used and were rotated randomly each day. Drivers weighing between 50 and 65 kg were also randomized each day. Training incorporated four sessions per week, starting at 10 min duration and gradually progressing to 45 min per session. The amount of daily exercise each horse received was recorded and the mean number of strides taken per horse for the entire training period was 47 402 strides, with a range between individuals from 20 832 to 81 312.

### Measurement of capsule shape

The right front hoof of all control and exercised horses was digitally photographed using a Panasonic VDR-M30 (Panasonic Consumer Electronics Company, Elgin, IL, USA) digital video camera with zoom lens before the 16-week training programme and after its completion (*c.* 129 days after the first set of pictures were taken).

Scaled digital photographs were taken in four different views: solar, dorsal, medial and lateral. For the dorsal view, horses stood on a flat, level surface and pictures were taken with the camera at a set height above the ground and a set distance in front of the hoof. All other pictures were taken with the hoof held off the ground. Medial and lateral pictures were taken with the camera lens parallel to and centred on the midpoint of the sole. For the solar pictures, the camera lens was perpendicular to the underside of the hoof and centred on its midpoint. Multiple pictures were taken in each view and the clearest images were downloaded onto a PC computer and loaded into Optimas version 6.5 imaging software (Bioscan, Inc., Edmonds, WA, USA) for measurement extraction.

Twenty-four linear and angular measurements were extracted from the digital images for each horse. Dorsal, medial, lateral and solar measurement diagrams can be seen in Fig. 1 (abbreviations in Table 1). These types of measurements have been used in previous experiments to quantify hoof capsule shape<sup>20</sup>, and we established their degree of repeatability prior to their first use in several works from our laboratory<sup>5,21,22</sup>. Variability in the relative accuracy

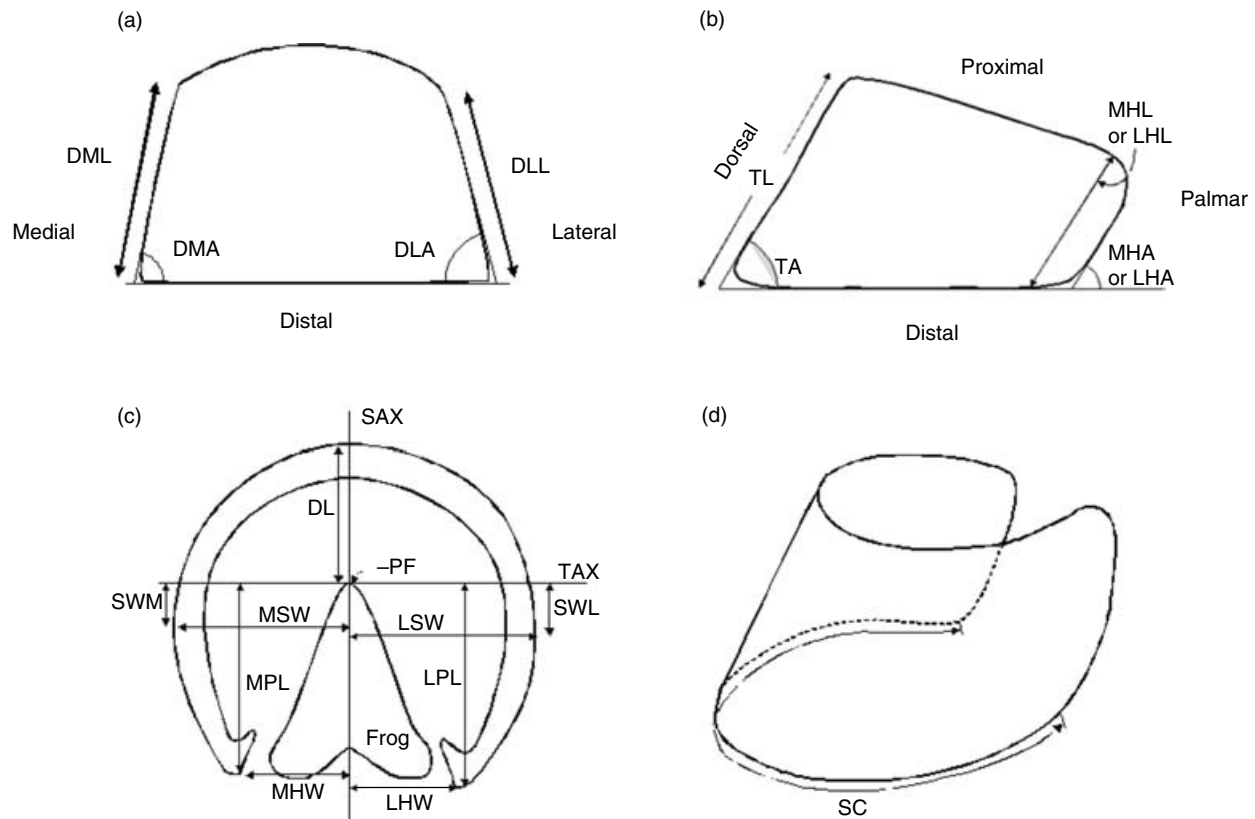


Fig. 1 Capsular measurements: (a) dorsal view, (b) lateral/medial view, (c) solar view and (d) solar circumference (SC). See Table 1 for abbreviations (modified from Thomason *et al.*<sup>4</sup>)

among these measurements will be returned to in the discussion. The same person extracted all measurements to ensure consistency.

### **Magnetic resonance imaging (MRI) and bone data collection**

We generally followed established and well-documented techniques for using magnetic resonance to image the equine digit and hoof<sup>23-26</sup>.

Prior to any MRI scans, shoes were removed and the right front digit was radiographed to ensure there was no metal debris in the hoof. After the exercise period, small metal filings in the nail holes caused imaging artefacts in some hooves. These were removed or minimized by reaming out the nail holes with a 1/8" drill bit, followed by cleaning with a pipe cleaner and filling with silicone. The few artefacts remaining were confined to the distal border of the wall (this problem did not arise prior to exercise, as most horses were not shod prior to the experiment). Immediately before each MRI scan, 15 cm of 2 mm catheter tube, filled with olive oil, was placed around the coronary band of the hoof as a marker. An L-shaped Plexiglas calibration gauge was positioned with the foot of the L parallel to the sole and the stem adjacent to the wall. The spacing and size of six oil-filled spherical

holes in the gauge were used to verify the linear calibration of the images provided by the MRI unit.

MRI of the right front hoof was performed for all control and exercised horses before the exercise regime began at day 0, and after the training period had concluded, between day 136 and day 167. All scans were conducted at the Ontario Veterinary College at the University of Guelph using a whole-body MRI scanner (1.5 T GE Sigma, General Electric Healthcare, Milwaukee, WI, USA). A custom four-coil-phased array designed to wrap closely around the hoof was constructed to enhance image quality.

The MR images from all feet were obtained using a 3D-FSPGR (Fast Spoiled Gradient-Recalled echo) pulse sequence. The resultant images were T1 weighted with 60 contiguous 1.5 mm-thick transverse slices and an in-plane resolution of 0.625 mm. Analysis was done on a GE Advantage Windows Workstation, software version 4.2, using the Volume Viewer program (General Electric Healthcare).

It was not possible accurately to reproduce hoof positioning within the MRI magnet, among horses and between pre- and post-exercise imaging sessions, for fear of injuring the horses. The acquisition planes of most MR images were, therefore, not exactly congruent with the anatomical planes of the distal phalanx. To correct this, each 3-D data set was

**Table 1** Abbreviations and definitions of reference markers and shape measurements made on the hoof capsule and distal phalanx (modified from Thomason *et al.*, 2001)

Abbreviation	Name and description of measurement or reference
SAX	Sagittal axis, midline reference axis of the hoof. Any line on a vertical plane through the midpoint of the heels palmarly and the tip of the extensor process of the distal phalanx dorsally, in solar view
PF	Point of the frog, a reference point on the sole, seen in solar view
TAX	Transverse axis, perpendicular to SAX through PF, in solar view
BDL	Bone dorsal length, length from the dorsal tip of the distal phalanx to the tip of the extensor process from mid-sagittal slice
BL	Body length, length from the solar surface at the tip of the distal phalanx to the articular surface of the navicular bone from mid-sagittal slice
BDA	Bone dorsal angle, angle between the dorsal aspect of the distal phalanx to the solar surface from mid-sagittal slice
EPH	Extensor process height, length from the articular surface of the navicular bone to the tip of the extensor process from mid-sagittal slice
BW	Bone width, widest measurement of the distal phalanx
DMA, DLA	Dorsal medial and lateral angles, between the abaxial aspects of the hoof wall and the bearing surface, in dorsal view
DML, DLL	Dorsal medial and lateral lengths, from the hairline to the ground, on the abaxial aspects of the hoof wall, in dorsal view
LHL, MHL	Lateral and medial heel lengths, from the hairline to the ground, parallel to the margin of the heel's heel, in lateral or medial view
LHA, MHA	Lateral and medial heel angles, between the palmar margin of the hoof wall at the respective heel and the ground, in lateral or medial view
DL	Dorsal length, measured dorsally from the point of the frog to the dorsum, in solar view
LPL, MPL	Lateral and medial palmar lengths, from the point of the frog to the tip of the respective heel, parallel to SAX, in solar view
LHW, MHW	Lateral and medial heel widths, from the sagittal axis, SAX, to the palmar margin of the bearing surface at the respective heel, in solar view
LSW, MSW	Lateral and medial sole widths, from SAX to the widest lateral and medial points of the hoof, in solar view
SWL, SWM	Sagittal position of widest medial point, measured dorsally or palmarly from the point of the frog parallel to SAX, in solar view
SC	Solar circumference, measured around the distal margin of the wall from the medial heel to the lateral heel, in solar view
TL	Toe length, length from the hairline along the dorsal surface to the tip of the hoof
TA	Toe angle, angle between ground surface and dorsal wall, averaged from lateral and medial views

manually rotated in the software, with views of all three orthogonal planes simultaneously visible on screen, until a true mid-sagittal plane and a dorsal plane through the widest point of the phalanx were obtained. Five linear measurements were extracted from the realigned images (Fig. 2, abbreviations in Table 1). Measurements were conducted in random order by horse and by the same person.

To examine the repeatability of manually rotating the images and making the measurements, the procedure was repeated for MRI made pre- and post-exercise for six hooves: three from the control group and three from the exercise group. Raw MRI from each hoof was rotated and a set of measurements made by the same observer on three occasions separated by a minimum interval of 4 days. These data were statistically analysed by intraclass correlation, as described below.

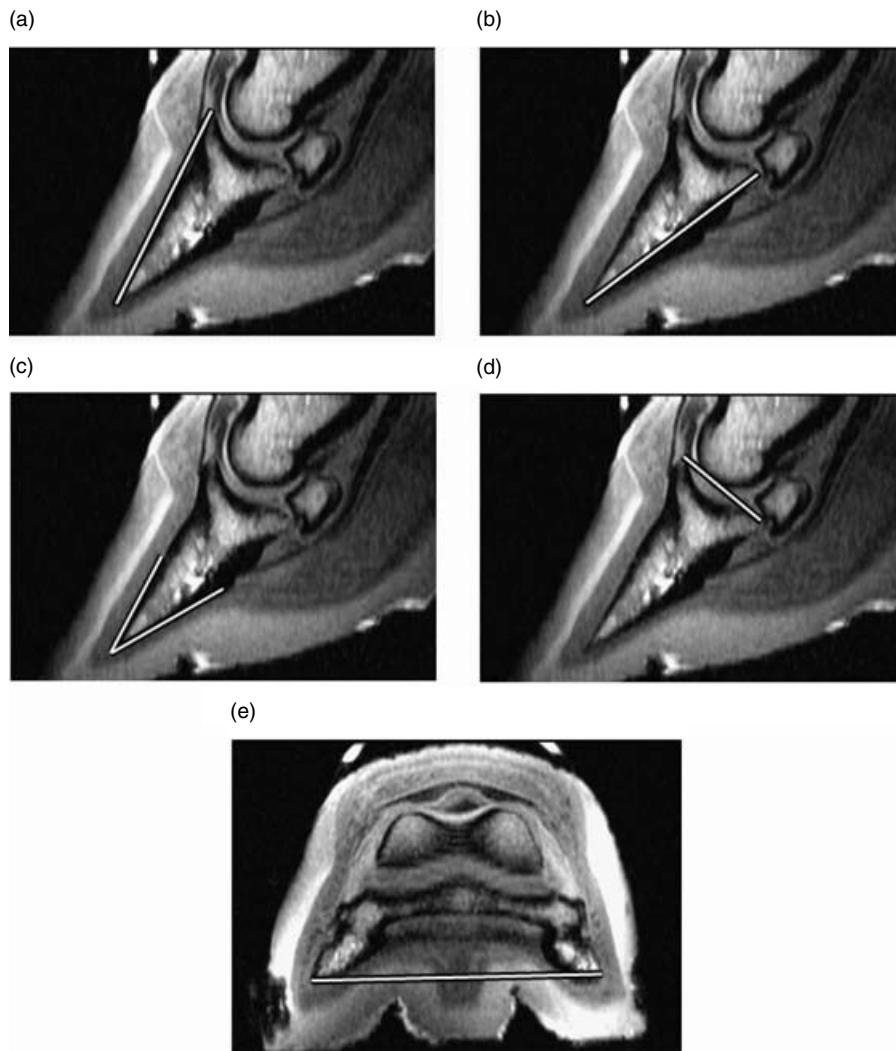
### **Statistical analysis**

Statistical analysis of all measurements was performed using SAS (SAS Institute, Cary, NC, USA). The sequence and purpose of all statistical tests was as follows, with details of each one given under subsequent subheadings: the data were first tested for normality, as this is a necessary criterion for subsequent tests, then for strength of agreement, to examine the

repeatability of image rotation and measurement accuracy. Changes of individual capsular and phalangeal measurements over the course of the experiment were then assessed, followed by a test of global shape change of the bone (which took all five phalangeal measurements into account simultaneously). Finally, the changes in all bone and capsule measurements were correlated pairwise with each other and the distribution of significant correlations compared between control and exercise groups. One purpose of this test was to assess whether the capsule and the bone changed shape in concert, and the other was to assess whether changes in all capsule variables were linked.

### *Preliminary test of normality*

All distal phalangeal and hoof capsule-shape data were tested for normal distribution, using the Anderson Darling test (Procedure Univariate in SAS,  $\alpha > 0.15$ ). Most non-normal data were transformed into normally distributed data through a number of transformations (natural log,  $\log_2$ ,  $\log_{10}$ , square roots, squaring or cubing). For data that could not be normalized, a signed-rank test was used in place of a Student's *t*-test. Subsequent tests were performed on the collected data where probability  $P < 0.05$  was considered significant.



**FIG. 2** Linear measurements extracted from MRI of the distal phalanx (in millimetres): (a) dorsal length of the bone, BDL, (b) body length, BL, (c) dorsal angle, BDA, (d) height of the extensor process, EPH and (e) bone width, BW

*Preliminary test of strength of agreement (intraclass correlation)*

To account for inaccuracy in rotating the MRI and making bone measurements, statistical analysis of the repeated measurements for six horses was analysed using a mixed linear model for intraclass correlation. This test measured the strength of agreement between these repeated measurements for those six horses' pre- and post-exercise measurements, with each variable separated. From this test, the variance due to differences between horses and the magnitude of variance due to treatment (i.e. exercise) were found. Residual variances were found as well, which take into account all the other possible errors that cannot be explained by horse or treatment, including the error in taking repeated measurements. The treatment variance found was divided by the treatment plus residual variances to calculate an intraclass correlation. These were then used as a relative measure of accuracy.

The effect of 'horse' was removed as it makes intuitive sense that there will be variation in measurements from horse to horse. The numbers generated were compared with a  $\kappa$  scale as follows: poor (0.00), slight (0.01–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80) and almost perfect (0.81–1.00)<sup>27</sup>. Although the divisions are arbitrary, they provide a useful benchmark for discussion of the accuracy of individual measurements.

*Changes in shape of hoof and bone*

Magnitudes of change were calculated for measurements made before and after exercise on the distal phalanx and capsule for each individual, and averaged within control and exercise groups. Significance of changes for each measurement was evaluated, within group, using a two-tailed paired Student's *t*-test for normally distributed data. A signed-rank test was used on

any data that could not be normalized with any transformation.

#### *Global shape change in the distal phalanx*

A multivariate analysis of variance (MANOVA) was performed (using SAS Procedure GLM, general linear model) on the differences in all five distal phalangeal measurements, from pre- to post-exercise, to test for global changes in bone shape during the exercise period. This was done separately for control and exercise groups.

#### *Bone and hoof capsule correlations*

Differences were calculated between pre- and post-exercise measurements of bone and capsule measurements. All resulting values were correlated with each other pairwise (using Procedure CORR in SAS).

## Results

Descriptive statistics for all measurements are shown in Table 2 for control and exercise groups, before and after the experiment.

#### *Preliminary test of normality*

All variables were normally distributed, except three for the control group (width of the distal phalanx (BW), lateral heel width (LHW) and location of the widest medial point of the sole in relation to the point of the frog (SWM) and two for the exercise group (dorsal length of the phalanx (BDL) and medial heel width of the capsule (MHW); Table 2: superscript 'nn'). Signed-rank tests replaced *t*-tests when these variables were involved.

#### *Preliminary test of intraclass correlation*

Repeatability of the image rotation and subsequent phalangeal measurements, as based on values of intraclass correlation (Table 3), were substantial for dorsal length of the bone (BDL), fair for the body length of the bone (BL) and bone width (BW), slight for height of the extensor process (EPH) and poor for the dorsal angle of the bone (BDA). These categorizations will be used in the discussion to qualify the presence or absence of significant changes in these variables, as described below.

#### *Hoof and bone measurements: changes in shape*

Toe length (TL) and toe angle (TA) are general indicators of capsule shape, and both increased in both groups during the experiment. For the control group exercise (Table 2a), mean TL increased slightly from  $8.5 \pm 0.38$  cm before exercise to  $8.8 \pm 0.75$  cm after. Mean TA increased from  $52.6 \pm 3.26^\circ$  before exercise to  $56.0 \pm 2.06^\circ$  after exercise. For the exercise group (Table 2b), TL was  $8.5 \pm 0.51$  cm before and

$9.2 \pm 0.68$  cm after, and TA was  $51.5 \pm 2.39^\circ$  before and  $54.26 \pm 1.23^\circ$  after exercise.

Out of the 50 pairs of before-and-after measurements made on the distal phalanges and hoof capsules of

**Table 2** Descriptive statistics (mean and standard deviation, STD) for (a) the control group and (b) the exercise group. Differences are shown between pre- and post-exercise means and expressed as a percentage of the pre-exercise value (percentage of change). Bone lengths and widths are in millimetres; capsular lengths and widths are in centimetres and angles are in degrees. Variables with non-normal distribution are indicated with a superscript 'nn'. Significant changes ( $P < 0.05$ ) are indicated by an asterisk

Variable	N	Pre-experiment		Post-experiment		Changes	
		Mean	STD	Mean	STD	Mean	STD
<i>(a) Controls</i>							
BDL	9	59.6	2.55	59.5	4.24	-0.1	2.40
BL	9	58.8	2.42	58.4	2.38	-0.4	0.99
BDA	9	33.3	4.27	36.0	3.97	2.7*	1.27
EPH	9	29.8	1.99	29.6	1.84	-0.2	0.91
BW <sup>nn</sup>	9	80.9	6.62	82.4	5.48	1.5	2.15
DLL	9	6.1	0.31	6.4	0.57	0.3	0.52
DML	9	6.2	0.41	6.3	0.48	0.2	0.56
DLA	9	78.7	4.92	78.2	3.69	-0.5	3.17
DMA	9	82.4	2.97	79.3	2.22	-3.1*	2.00
LHL	9	3.7	0.77	4.0	0.86	0.3	0.91
LHA	9	46.7	6.87	53.4	5.51	6.7	11.04
MHL	9	3.7	0.65	4.2	0.45	0.6	0.94
MHA	9	46.5	3.38	48.5	5.98	2.0	4.51
DL	9	5.0	0.27	5.0	1.13	0.0	1.31
MPL	9	8.1	0.74	7.8	0.86	-0.3	1.24
LPL	9	8.1	0.59	7.8	0.98	-0.3	1.07
MHW	9	3.0	0.60	3.3	0.80	0.3	0.62
LHW <sup>nn</sup>	9	2.9	0.50	3.1	0.57	0.2	0.38
MSW	9	6.0	0.45	5.8	0.66	-0.2	0.40
LSW	9	6.1	0.54	6.0	0.74	-0.1	0.41
SWM <sup>nn</sup>	9	2.0	0.79	1.6	1.11	-0.4	1.42
SWL	9	2.0	0.73	1.7	1.35	-0.3	1.38
SC	9	35.4	1.24	33.9	2.29	-1.5*	1.81
TL	9	8.5	0.38	8.8	0.75	0.3	0.44
TA	9	52.6	3.36	56.0	2.06	3.4*	3.49
<i>(b) Exercise group</i>							
BDL <sup>nn</sup>	9	62.2	3.05	63.1	2.19	0.9*	2.06
BL	9	60.2	2.44	61.7	2.88	1.4*	0.88
BDA	9	31.9	3.36	30.3	3.72	-1.6*	1.96
EPH	9	30.9	2.50	30.8	2.04	-0.1	1.52
BW	9	86.1	3.83	87.1	3.98	1.0	1.45
DLL	9	6.2	0.47	6.4	0.77	0.2	0.56
DML	9	6.1	0.68	6.5	0.74	0.4	0.65
DLA	9	76.6	3.99	78.7	2.43	2.0	4.07
DMA	9	79.6	5.32	78.1	2.51	-1.5	5.08
LHL	8	3.6	1.02	4.3	0.55	0.6	0.92
LHA	8	46.7	7.97	47.8	4.85	1.3	5.92
MHL	9	3.5	0.57	4.4	0.33	1.0*	0.42
MHA	9	45.8	6.87	47.5	5.31	1.7	6.54
DL	9	5.0	0.69	4.7	0.57	-0.2	0.66
MPL	9	7.8	0.35	7.5	0.70	-0.3	0.50
LPL	9	8.3	0.57	7.5	0.60	-0.6*	0.47
MHW <sup>nn</sup>	9	3.2	0.76	3.0	0.53	-0.1	0.46
LHW	9	2.9	0.55	3.2	0.42	0.3	0.51
MSW	9	6.3	0.68	6.0	0.32	-0.3	0.49
LSW	9	6.6	0.42	6.2	0.32	-0.4*	0.15
SWM	9	2.0	0.60	2.0	0.73	0.0	0.67
SWL	9	2.2	0.60	2.1	0.67	-0.1	0.94
SC	9	36.0	1.99	34.7	2.24	-1.2*	1.29
TL	9	8.5	0.51	9.2	0.68	0.7	0.64
TA	9	51.5	2.39	54.3	1.23	2.8	2.48

**Table 3** Strength of agreement of repeated measurements from six horses for each distal phalangeal measurement

Variable	Intraclass Correlation	Strength of agreement
Dorsal length, BDL	0.797	Substantial
Horizontal length, BL	0.3208	Fair
Dorsal angle, BDA	0	Poor
Height of extensor process, EPH	0.1793	Slight
Width, BW	0.4006	Fair

exercise and control groups, 15 showed significant changes ( $P < 0.05$ ): three measurements in both the controls and exercised horses, two in the controls alone and six in the exercised group alone (Table 2: asterisks). Changing significantly in both groups were: BDA increased in the exercise group ( $P = 0.036$ ) and decreased in the controls ( $P = 0.002$ ); SC of the capsule decreased in both ( $P = 0.021$ , exercise;  $P = 0.037$ , control) and TA increased in both ( $P = 0.001$ , exercise;  $P = 0.019$ , control). Changing significantly only in the control group were: width of the distal phalanx (BW, increased,  $P = 0.039$ ) and angle of the medial capsule wall (DMA, decreased,  $P = 0.002$ ). Changing significantly only in the exercise group were: dorsal bone length (BDL, increased,  $P = 0.039$ ), body length of the bone (BL, increased,  $P = 0.001$ ), medial heel length in medial view (MHL, increased,  $P < 0.0001$ ), lateral heel length from the point of the frog in solar view (LPL, decreased,  $P = 0.005$ ), maximum width from the point of the frog to the lateral wall (LSW, decreased,  $P < 0.0001$ ) and toe length (TL, increased,  $P = 0.009$ ).

### Bone measurements: global shape change

The MANOVA based on all five measurements of the distal phalanx indicated an overall significant change for the controls ( $F = 11.41$ ,  $P = 0.0176$ ), but no overall significant change for the exercise group horses ( $F = 5.63$ ,  $P = 0.0594$ ).

### Correlations among hoof and bone measurements

#### Correlations among changes within groups

The 25 differences between pre- and post-exercise measurements of capsule and bone (Table 2) represented 300 pairwise combinations for examining correlations. Out of this possible maximum, 26 correlations were significant ( $P < 0.05$ ) for the control horses and 13 for the exercise group (Table 4, Fig. 3). In the control group, 16 out of the 26 significant correlations involved measurements of the heels as one of the pair. In the exercise group, 8 out of the 13 included at least one bone measurement, while a bone measurement was involved in only two of the control-group correlations.

## Discussion

The main objectives of this study were to examine the shape of the distal phalanx over a period of regular exercise and to assess whether any changes found correlated with those in the hoof capsule.

### Discussion of the objectives

#### Objective 1: does exercise cause changes in the shape of the distal phalanx?

Significant changes in measurements of the distal phalanx were small, generally  $< 2\%$  of their initial value and occurred in both groups. These results indicate that the distal phalanx is essentially a stable platform.

A small change in bone width (BW,  $P = 0.039$ ) occurred in the controls, and in dorsal bone length (BDL,  $P = 0.039$ ) and body length (BL,  $P = 0.001$ ) for the exercise group (a shared change in bone dorsal angle, BDA, is omitted from this discussion,

**Table 4** Significant correlations among shape and bone difference measurements for (a) control group and (b) exercise group

Variable 1	Variable 2	R-value	P-value
<i>(a) Control</i>			
BDL	MHL	0.743	0.022
BDA	LSW	-0.790	0.011
DLL	DML	0.842	0.004
DLL	DMA	0.674	0.047
DLL	LHA	0.684	0.042
DMA	LHA	0.733	0.025
DMA	TA	0.682	0.043
LHL	MHL	0.802	0.009
LHL	MHW	0.693	0.038
LHL	LHW	-0.771	0.015
LHA	MHA	0.753	0.019
LHA	DL	-0.712	0.031
MHL	LHW	-0.786	0.012
DL	LPL	-0.747	0.021
DL	SWM	-0.883	0.002
DL	SWL	-0.904	0.001
MPL	LPL	0.752	0.019
MPL	LHW	0.738	0.023
MPL	SWL	0.716	0.030
LPL	SWM	0.873	0.002
LPL	SWL	0.774	0.014
MHW	TA	0.857	0.003
MSW	LSW	0.820	0.007
MSW	SC	0.686	0.041
LSW	SC	0.730	0.026
SWM	SWL	0.859	0.003
<i>(b) Exercise</i>			
BDL	MHW	0.737	0.023
BDL	SC	-0.682	0.043
BL	DMA	0.881	0.002
BDA	MHA	0.672	0.048
BDA	SWM	-0.710	0.032
EPH	BW	0.671	0.048
EPH	DLA	-0.671	0.048
BW	MHA	-0.735	0.024
DLL	LHW	0.703	0.035
DLL	TL	0.774	0.014
DLA	MPL	-0.701	0.036
MHL	TA	-0.735	0.024
TL	TA	-0.715	0.030

		BONE					TOE						HEELS						QUARTERS							
		BDL	BL	BDA	EPH	BW	DL	DLL	DML	DLA	DMA	TL	TA	LHL	LHA	MHL	MHA	MPL	LPL	MHW	LHW	MSW	LSW	SWM	SWL	SC
BONE	BDL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	BL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	BDA	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	EPH	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	BW	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
TOE	DL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	DLL	.	.	.	.	.	.	.	+	.	+	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	DML	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	DLA	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	DMA	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	TL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
HEELS	LHL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	LHA	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	MHL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	MHA	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	MPL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	LPL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	MHW	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	LHW	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
QUARTERS	MSW	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	LSW	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	SWM	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
	SWL	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
SC	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		

FIG. 3 Distributions of statistically significant correlations among shape and bone difference measurements post-experiment ( $P < 0.05$ ). Control group data are upper right and exercise group data lower left. Variables are ordered by bone and hoof region. Symbols: +, significant positive correlation; -, significant negative correlation

owing to the low accuracy in repeating this measurement; Table 3). These significant changes are intriguing, especially the increased bone width in the controls, and because the exercise group showed small changes in bone length rather than in width. If the control horses had previously been in training, cessation of that exercise would have induced bone remodelling<sup>28</sup>, though this does not explain why bone width increased. The trimming and shoeing regime followed would have represented a stimulus to all of the horses, as it would certainly have differed in some aspects from their prior treatment, and this may underlie the width change in the controls. The differences between groups suggest that the stimulus of exercise also promoted the small changes in bone length. Notwithstanding these differences, the low magnitudes of change (from 0.1 to 1.5 mm) support the conclusion that the bone is essentially stable.

An ability of the distal phalanx to resist changes in shape is appropriate, given its functions of supporting the capsular and acting as a primary determinant of capsular shape. The olecranon process of the ulna and calcaneus are similarly resistant, for good functional reasons. But alternative explanations are possible for the minimal change in shape found here, and

we need to acknowledge them. Remodelling induced by the exercise may have acted in changing bone density, which is not well assessed by MRI - but had less effect on overall shape. The horses were all skeletally mature, and younger horses have a greater ability to adapt to mechanical loading in bones than older horses<sup>9,29,30</sup>. Finally, the low intensity of exercise may have produced low rates of remodelling<sup>30</sup>. In future studies, immunostaining could be used to indicate rates of bone remodelling, to compare activity between the distal phalanx and other bones of the digit.

*Objective 2: do changes in bone and capsule correlate with each other?*

Significant changes occurred in only a few capsular measurements and were small for the most part, as was found for the bone measurements. It was, therefore, hardly surprising that the results gave essentially no indication of concerted and correlated changes in the shapes of bone and capsule. On the other hand, the control group showed a number of correlations among changes in capsule shape, and more than in the exercise group. Given the care taken to minimize trimming bias, it is unlikely that

this finding is the result of systematic influence by the farrier. It raises the possibility that reduced exercise allows the capsule to grow more uniformly, promoting correlation among certain capsule measurements. During exercise, variability of loading among individuals may tend to disrupt that uniformity. These speculations certainly need further investigation before being stated more definitively.

### Issues with the methods

The use of a farrier was potentially a major confounding factor for a study of this kind, and care was taken to minimize any systematic bias that might have been introduced. The primary argument against the occurrence of systematic bias is in the data of Table 4 and Fig. 3. As stated above, the marked difference between control and exercised animals in the number and distribution of correlations among capsule changes argues strongly against such bias.

The repeatability and accuracy of the phalangeal measurements was a second issue and there was good evidence that all were not precisely repeatable (Table 3). The degree of change observed in the bone was close to the limit of resolution of the MRI. This fault is mitigated because the primary finding of small changes certainly leads to the conclusion of phalangeal stability, which is not repudiated by some inaccuracy in the measurements.

### Conclusions

1. The distal phalanx forms a stable platform under repetitive moderate loads that may be expected to stimulate bone remodelling.
2. Small changes in individual measurements of the bone occurred in both controls and exercised horses, suggesting that they are not strongly linked to exercise.
3. Changes in measurements of the hoof capsule do not correlate with those in the bone.
4. Stronger patterns of correlation were found among capsular changes in the controls than in the exercise group, implying that exercise may in some way reduce the architectural coherence of the hoof.

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