J. Anat. (2006) **209**, pp597–609 doi: 10.1111/j.1469-7580.2006.00640.x

Factors influencing osteological changes in the hands and fingers of rock climbers

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Abstract

This study examines the osteological changes in the hands and fingers of rock climbers that result from intense, long-term mechanical stress placed on these bones. Specifically, it examines whether rock climbing leads to metacarpal and phalange modelling in the form of increased cortical thickness as well as joint changes associated with osteoarthritis. This study also attempts to identify specific climbing-related factors that may influence these changes, including climbing intensity and frequency of different styles of climbing. Radiographs of both hands were taken for each participant and were scored for radiographic signs of osteoarthritis using an atlas method. Total width and medullary width were measured directly on radiographs using digital calipers and used to calculate cross-sectional area and second moment of area based on a ring model. We compared 27 recreational rock climbers and 35 non-climbers for four measures of bone strength and dimensions (cross-sectional area, second moment of area, total width and medullary width) and osteoarthritis. A chi-squared test for independence was used to compare climber and non-climber osteoarthritis scores. For each measure of bone strength climbers and non-climbers were compared using a MANOVA test. Significant MANOVA tests were followed by principal components analysis (PCA) and individual ANOVA tests performed on principal components with eigenvalues greater than one. A second PCA was performed on the climber subsample and the first principal component was then used as the dependent variable in linear regression variable selection procedures to determine which climbing-related variables affect bone thickness. The results suggest that climbers are not at an increased risk of developing osteoarthritis compared with non-climbers. Climbers, however, do have greater cross-sectional area as well as second moment of area. Greater total width, but not meduallary width, indicates that additional bone is deposited subperiosteally. The strength of the finger and hand bones are correlated with styles of climbing that emphasize athletic difficulty. Significant predictors include the highest levels achieved in bouldering and sport climbing.

Key words bone modelling; cortical bone; mechanical stress; osteoarthritis.

Introduction

In recent years the popularity of recreational and competitive rock climbing has been on the rise, and as a result there has been an increase in reports on climbing-related injuries (Bannister & Foster, 1986; Bollen & Gunson, 1990; Bollen, 1990a,b; Cole, 1990; Della Santa & Kunz, 1990; Heuck et al. 1992; Shea et al. 1992; Hochholzer et al. 1993; Robinson, 1993; Haas & Myers, 1995; Rooks et al. 1995; Holtzhausen & Noakes, 1996; Wyatt et al. 1996; Jebson & Steyers, 1997; Rooks, 1997; Schaeffer et al. 1998; Klauser et al. 1999). Many are reports on acute and overuse soft tissue injuries, although there is growing interest in climbing's effect on long-term joint health as well as on bone modelling (Bollen & Wright, 1994; Rohrbough et al. 1998; Schöffl et al. 2004). Rock climbers, especially at more advanced levels, routinely expose their fingers and hands to intense mechanical stress by supporting part or all of their body weight on their fingers. Most climbers are quite aware of the potential for soft tissue injuries, but also express concern regarding osteoarthritis (OA). These concerns are well founded because it is known

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Accepted for publication *22 June 2006*

that heavy or repetitive mechanical stress can have adverse effects on joint health (Simon, 1999). Just as well established is the link between mechanical stress and bone modelling and remodelling (for a review see Pearson & Lieberman, 2004). Rock climbing provides an opportunity to evaluate the modelling response of bone to mechanical stress.

Although some joint loading may have protective effects on finger health (Solovieva et al. 2005), continual overloading can lead to joint impairment (Felson et al. 2000). The relationship between sports and OA is well established and appears to be most related to direct, high-intensity joint impact and torsion (Kujala et al. 1995; Spector et al. 1996; Buckwalter & Lane, 1997; Coggon et al. 1998). Although climbing rarely involves joint impact, the compressive loads on some finger joints can be intense and joint torsion is frequent. Previous studies have found very different frequencies of OA among rock climbers compared with control samples (Bollen & Wright, 1994; Rohrbough et al. 1998; Peters, 2001; Schöffl et al. 2004).

In addition to joint changes, the mechanical stress incurred during rock climbing may be sufficient to stimulate the deposition of new bone. There is a great deal of interest in the effect of mechanical stress on long bone cross-sectional geometry, because bone geometry is used frequently by anthropologists to infer activity patterns (Ruff et al. 1999; Stock & Pfeiffer, 2001; Trinkaus & Ruff, 1999a,b). Previous work has found increased cortical thickness in the hands and fingers of rock climbers compared with a paired control sample (Bollen & Wright, 1994; Schöffl et al. 2004).

The relationship between mechanical stress and modelling, however, is an immensely complex one that is mediated by several factors. In a review of bone modelling and remodelling, Pearson & Lieberman (2004) conclude that the ubiquitous invocation of Wolff's law by functional morphologists is inappropriate because it does not provide an adequate description of the cortical bone response. Instead, they advocate more complex equilibrium and optimization models, which include ontogenetic age, skeletal location and haversian remodelling, to describe the total bone response more accurately. The complexities of these proposed relationships mandate that modelling and remodelling responses be examined separately for ontogenetic stages and skeletal elements.

This study examines two potential effects, OA and bone modelling, of rock climbing on metacarpals and finger phalanges by comparing a sample of recreational rock climbers with a matched (weight and height) group of non-climbers. First, the mechanical stress generated in the joints during rock climbing may contribute to a higher incidence of OA in rock climbers. Secondly, the mechanical stress associated with rock climbing may induce bone deposition to enhance strength. Because of the variety of hand positions rock climbers utilize, it is likely that they subject their hands and fingers to various combinations of compressive, tensile, bending and torsional stresses. Compressive and tensile strength are both proportional to cross-sectional area, while bending and torsional strengths are proportional to second moment of area and polar moment of inertia, respectively (Ruff, 2000). We expect that cross-sectional area, second moment of area and polar moment of inertia should be greater as a result of rock climbing and directly related to stress levels.

Although other studies have noted changes in the hands and fingers of rock climbers, this study expands on previous work in two main ways. First, we examine multiple measures of bone dimensions to estimate bone strength and to discern the location (subperiosteal or endosteal) of bone deposition. Secondly, we attempt to identify climbing-related factors that may contribute to modelling and OA. Rock climbing is a multifaceted sport and several distinct types or styles of rock climbing are recognized. To illustrate how these different styles and levels of climbing might influence osteological changes, a brief description of different climbing styles and the difficulty rating systems follows.

Three styles of rock climbing were investigated in this study: sport climbing, traditional climbing and bouldering. These types of rock climbing share the common feature that the climber makes progress up the rock using only the body (generally hands and feet, although knees, elbows, hips as well as other body parts are considered acceptable). The 'ethic' for these styles dictates that the climber may not use protection equipment or mechanical devices to make upward progress and such equipment is only used for safety in the event of a fall. The difference between these styles is mainly in the type of protection used to catch a falling climber.

In both sport climbing and traditional climbing, a rope is attached to protection points along the length of the 'route' (a specific section of rock). During sport climbing, as the climber ascends, he or she secures the rope to regularly spaced bolts that are permanently affixed in the rock. The bolt protection greatly enhances safety and allows the climber to focus almost entirely on the athletic aspects of the sport. Emphasis in sport climbing is often on pushing physical limits and attempting more difficult routes. In traditional climbing, the climber attaches the rope to specially designed equipment that must be affixed in the rock while ascending, and these pieces of equipment serve as the points of protection. This style demands great skill and time for affixing these protection points, because if not done correctly the protection will become dislodged and will not arrest a falling climber. Because a greater amount of the climber's attention must be directed towards protection (as compared with sport climbing), the athletic aspect is of lesser emphasis. Thus, climbers are generally able to attain a higher level of difficulty in sport climbing than they can in traditional climbing. Bouldering is rock climbing on short pieces of rock (usually boulders as the name implies) with use of a transportable foam mat to cushion the climber when they fall. Because of the relatively low height and lesser inherent danger, the emphasis is often on athletic difficulty.

We also investigated two activities related to rock climbing. The first is gym climbing, which can either be of the bouldering or sport climbing type, but is carried out on artificial climbing structures. The second is hand- and finger-specific exercises, which are used by many climbers to enhance hand and finger strength.

To help climbers locate a route of appropriate difficulty, each climbing route has an associated difficulty rating called a 'grade'. Although this rating is a consensus of climbers' opinions, several objective factors influence the grade of a route independently. These factors include the size of the hand and foot placements (hand-holds/foot-holds), distance between hand-holds or foot-holds, degree of overhang of the rock and frictional coefficient of the rock. Routes that are not overhanging, have large hand-holds and foot-holds, short distances between holds and highly textured rock receive easier grades than routes characterized by small holds that are far apart on smooth, radically overhanging rock (Fig. 1).

Sport and traditional climbing routes are rated, in North America, using the Yosemite Decimal System. This is an open-ended scale and routes currently range from 5.0 (read five-zero) to 5.15 (read five-15) with additional subgrades (a, b, c or d) for 5.10 and above. Lower numbers after the decimal point reflect easier climbs and higher numbers reflect greater difficulty. Note, 5.1 (five-one) does not equal, and is significantly easier than 5.10 (five-10). Bouldering routes, in North America, are graded on a different scale called the V-scale. This scale ranges from V0 to V15, with lower numbers representing easier sections of rock.

Materials and methods

Data collection

Twenty-seven climbers and 35 non-climbers were recruited for participation in this study following a protocol approved by the Human Subjects Review Board at the University of Tennessee. Participants were asked to complete a questionnaire that included personal bio-relevant data (mass, height and age) as well as information concerning participation in rock climbing (years of participation, types of climbing engaged in, frequency and highest level of difficulty achieved in different types of climbing). Highest levels of climbing in sport and traditional climbing were converted to an interval scale.

In addition to the questionnaire, a posterior–anterior radiograph of the right hand and a lateral radiograph of the left hand were taken for each participant with a Trex Hologic X-ray machine and standard film-to-tube distance of 40 inches. All postero–anterior radiographs were scored using a single-blind approach (P.A.K.) for the radiographic changes associated with OA using an atlas method (Altman et al. 1995). These radiographic signs include marginal osteophytosis, joint space narrowing, sclerosis and subchondral cysts. An unaffected site was scored as 0, and possible, definite or severe involvement was scored as 1, 2 or 3, respectively. Three joints were scored for each ray. The carpal–metacarpal, metacarpal–phalangeal and interphalangeal joints were scored for the thumb. For the fingers, the metacarpal–phalangeal and both interphalangeal joints were scored. A randomly selected subset of ten individuals was scored a second time and a kappa test for intraobserver reliability indicates high repeatability (Kappa coefficient = 0.92, Z-score = 12.23, $P < 0.0001$).

Total bone and medullary width were measured for 12 bones in each radiograph using digital calipers by one of us (A.M.C.). The metacarpals and proximal and medial phalanges of the second to fifth rays were measured from the radiograph of the right hand

Fig. 1 Examples of variables that affect climbing difficulty. (A) Large hand-hold; (B) small hand-hold; (C) vertical face; (D) overhanging face; (E) short distance to next hand-hold; (F) long distance to next hand-hold. Features A, C and E decrease difficulty while B, D and F increase difficulty.

radiograph. The proximal, medial and distal phalanges of the second to fifth rays were measured on the left hand radiograph. Metacarpal measurements were taken at midshaft (Roy et al. 1994), while proximal and medial phalanges were measured at two-thirds of the shaft length from the proximal end following Bollen & Wright (1994). Distal phalanges on lateral radiographs were measured just proximal to the apical tuft. Replicate total width measurements were taken for 20 participants (A.D.S.), and a MANOVA test of interobserver reliability did not reveal a significant difference (Wilks' lambda, $F = 0.40$, $P = 0.98$).

Four bone dimensions were calculated as measures of bone strength and to determine the location (subperiosteal/endosteal) of bone modelling in the fingers. Cross-sectional area was calculated for each bone using the ring model described by Roy et al. (1994) and provides a measure of the compressive and tensile strength of the bone. Second moment of area, which is proportional to bending strength, was also calculated using the ring model. The second moment of area was also used as a measure of torsional strength because in a circular ring the polar moment of inertia, which is proportional to torsional strength, is simply twice the second moment of area (Roy et al. 1994). Total bone width and medullary width were used to determine the location of bone (subperiosteal/endosteal) modelling. All bone measures were scaled by body mass prior to analyses. The linear measurements were scaled by reported body mass$^{0.33}$ and area was scaled by reported body mass$^{0.67}$. Second moment of area was scaled by the product of body mass and bone length as recommended by Ruff (2000).

Analyses

Because the prevalence and severity of OA were low, the OA scores were dichotomized to either 0 (no radiographic signs) or 1 (any radiographic sign). Climbers and non-climbers were compared using a chi-squared test for independence, testing the null hypothesis that climbers and non-climbers had the same levels of OA development, and as an alternative considered the hypothesis that climbers and non-climbers were statistically different. To examine which finger joints contributed to group differences, we regressed group membership against the OA scores for each joint using logistic regression.

Climbers and non-climbers were compared for the four measures of bone dimension (area, second moment of area, total width and medullary width) using individual multivariate analysis of variance (MANOVA) tests. We tested the null hypothesis that no group differences exist, and considered the alternative that significant group differences are present. We followed each significant MANOVA test with a principal component analysis (PCA) performed on the entire sample and retained only those components with eigenvalues greater than one for further analysis. We then compared the principal component scores for climber and non-climbers using multiple ANOVA tests. A Bonferroni adjustment was made to the significance level ($\alpha = 0.0025$) for all between-group comparisons to control for type-one errors associated with multiple tests.

To understand how different styles and length of participation in climbing might influence bone strength and dimension, we followed significant MANOVA tests with an additional PCA using only the climber subset. We then used the first principal component as the dependent variable in a linear regression analysis to determine which, if any, climbing variables were significant predictors. We examined nine single-variable models: years of participation in rock climbing, hours of sport climbing per week, hours of traditional climbing per week, hours of bouldering per week, highest difficulty level sport climbing, highest difficulty level traditional climbing, highest difficulty level bouldering, hours of grip training (hand and finger exercises) per week and hours climbing on indoor gyms per week. In the case that multiple variables were significant predictors we used partial correlation analysis to determine which of the independent variables have a stronger correlation with the first principal component of the measures of bone strength.

In cases where participants did not provide hours of climbing style, the hours of participation was recorded as zero. In cases where participants did not provide information on highest level of climbing achieved, we treated this as missing data and the case was removed from the regression analysis.

Results

Sample

Summary statistics for the mass, height and age data for the entire sample are provided in Table 1. Climber

Table 1 Summary statistics for climbers and non-climbers

Group	Age (years)			Height (cm)			Mass (kg)		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Climber	28.8	8.76	19–55	175.5	10.48	157.5–190.5	65.33	11.93	43.09–88.45
Non-climber	23.3	4.35	18–35	173.6	10.83	152.4–190.5	70.98	14.22	43.09–95.25

Table 2 Summary statistics of climbing-related factors for climbers

Variable	Average	Range
Years of climbing	7.5	< 1–18
Highest level in bouldering	V6	V1–V12
Highest level in sport climbing	5.12c	5.9–5.14b
Highest level in traditional climbing	5.9	5.6–5.12d
Hours of bouldering per week	3.94	0–18
Hours of sport climbing per week	11.44	0–30
Hours of traditional climbing per week	1	0–12
Hours of gym climbing per week	3.76	0–8
Hours of hand exercises per week	0.76	0–3

Table 3 Results from chi-squared test for independence for OA and group membership

	Non-climber	Climber
No OA	Observed = 6	Observed = 15
	Expected = 11.855	Expected = 9.1452
OA	Observed = 29	Observed = 12
	Expected = 23.145	Expected = 17.855

$\chi^2 = 10.04$, $P = 0.0015$.

Table 4 Logistic regression of group membership dependent on OA scores for 15 finger joints

Joint	R^2	Slope	Intercept	P
DIP2	0.0142	–1.160	–0.2188	0.3570
DIP3	0.0110	–0.744	–0.7445	0.4178
DIP4	0.0185	–1.118	–0.1242	0.2914
DIP5	0.0000	–0.072	–0.5848	0.9694
PIP2	0.0232	–1.182	–0.2703	0.2369
PIP3	0.0452	–2.381	–0.0938	0.0970
PIP4	0.0315	–1.740	–0. 1718	0.1678
PIP5	0.0207	–1.957	–0.3404	0.2642
MCP2	0.0012	0.634	–0.6338	0.7920
MCP3	0.0213	5.273	–0.6780	0.2583
MCP4	0.0213	5.273	–0.6780	0.2583
MCP5	No variance			
IP1	0.2756	–4.787	1.7232	< 0.0001
MCP1	0.0315	–2.735	–0.3282	0.1676
CMC1	0.0096	1.408	–0.7519	0.2311

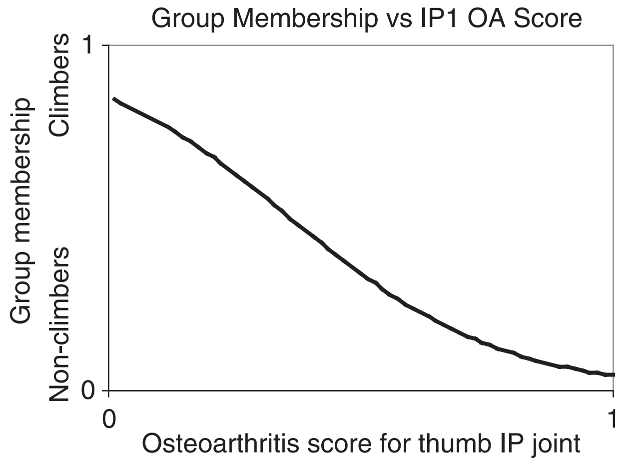

Fig. 2 Logistic regression of group membership on OA score for thumb interphalangeal joint.

data, including hours and levels achieved in specific facets of climbing, are provided in Table 2.

Osteoarthritis

Analyses revealed that climbers and non-climbers differed significantly with respect to the development of OA, although no individual in either group exhibited subchondral cysts or sclerosis and only one person (Subject 3) had a score of 3 (distal interphalangeal joint of 3rd phalange). Interestingly, it was the non-climbers rather than the climbers that had a higher incidence of OA compared with expected values (Table 3). Forty-four per cent of climbers compared with 82% of non-climbers had some evidence of osteophytosis and/or joint space narrowing (Table 3). Logistic regression analysis suggested that only one finger joint, the distal joint of the thumb, was a significant predictor of group membership ($R^2 = 0.2756$, $F = 22.82$, $P < 0.0001$) although its predictive ability was low. The estimate of the regression slope was negative ($m = -4.787$), indicating that higher incidence of OA in this joint was associated with the non-climbers (Table 4, Figs 2 and 3).

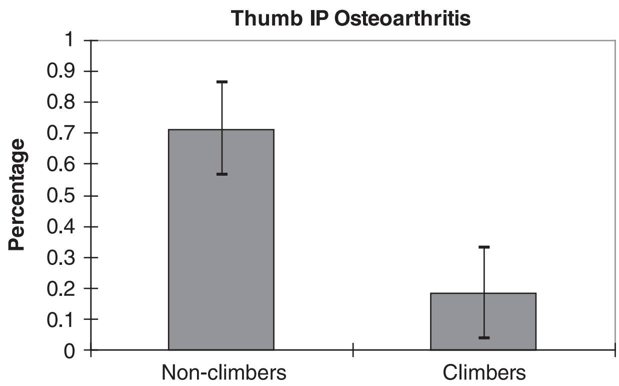

Fig. 3 Prevalence of OA in interphalangeal thumb joint. Bars, percentage of group with signs of OA; lines, 95% confidence interval.

Table 5 Results from MANOVA tests comparing climbers and non-climbers for four measures of bone strength and dimension

Comparison	*F*	*P*
Total width	3.24	0.0008
Medullary width	1.97	0.0335
Cross-sectional area	4.91	< 0.0001
Second moment of area	3.45	0.0004

Bone dimensions and strength

Climbers and non-climbers differed in second moment of area (Wilks' lambda, $F = 3.45$, $P = 0.0004$), cross-sectional area (Wilks' lambda, $F = 4.91$; $P < 0.0001$) and total width (Wilks' lambda, $F = 3.24$, $P = 0.0008$), but not for medullary width (Wilks' lambda, F 1.97, $P = 0.0335$) (Table 5). Because a statistical difference was not found between climbers and non-climbers with respect to medullary width additional analyses were not performed.

Results from the PCAs are provided in Tables 6–8. The first and second components from the PCA performed on the combined climber/non-climber sample are plotted in Fig. 4(a)–(c). In all three measures of bone strength, ANOVA tests performed on the first principal component scores revealed between-group differences (Tables 9–11). In all measures climbers had higher first principal component scores than non-climbers. Subsequent tests on the other retained components did not reveal any group differences for each measure of bone strength (Tables 9–11).

Table 6 PCA results from second moment of area data (climber/non-climber combined sample)

	Prin1	Prin2	Prin3	Prin4
Eigenvalues	11.97	2.45	1.55	1.30
(Proportions)	(0.4988)	(0.1023)	(0.0646)	(0.0541)
P-MC2	0.203367	0.013334	−0.129130	0.132992
P-MC3	0.195470	−0.073115	−0.066276	0.212591
P-MC4	0.191662	0.094344	−0.099009	0.390264
P-MC5	0.189239	0.200785	−0.127235	0.209847
P-PP2	0.205816	0.299805	0.059424	−0.080015
P-PP3	0.228499	0.235728	−0.082607	−0.088404
P-PP4	0.235403	0.287508	−0.016730	0.027528
P-PP5	0.176550	0.326583	0.083558	0.324307
P-MP2	0.190800	0.183308	0.144904	−0.475165
P-MP3	0.201220	0.226174	0.075173	−0.338527
P-MP4	0.222230	0.206066	0.062137	−0.195981
P-MP5	0.183216	0.172100	−0.059445	0.082631
L-PP2	0.236059	−0.100946	−0.130455	−0.077735
L-PP3	0.236049	−0.155154	−0.267577	−0.049749
L-PP4	0.229032	−0.201777	−0.274831	−0.058399
L-PP5	0.210262	−0.167905	−0.064231	0.332230
L-MP2	0.223419	−0.182059	−0.095448	−0.114327
L-MP3	0.215430	−0.294519	−0.020858	−0.172360
L-MP4	0.222619	−0.307529	−0.121096	−0.088960
L-MP5	0.218707	−0.178222	−0.059325	−0.038985
L-DP2	0.168087	−0.102995	0.340078	−0.022694
L-DP3	0.166300	−0.262690	0.395262	−0.041420
L-DP4	0.139052	−0.150410	0.443451	0.187250
L-DP5	0.172660	−0.045002	0.486564	0.152304

P = posterior/anterior radiograph of right hand; L = lateral radiograph of left hand; MC = metacarpal; PP = proximal phalange; MP = middle phalange; DP = distal phalange; Number = Ray.

Regression analysis

The PCA performed on the climber subset second moment of area data resulted in a first principal component that accounted for 0.3626 of the variation. Two climbing variables were found to be significant predictors ($\alpha = 0.05$) of the first principal component, while an addition variable was nearly significant. These variables were highest level of difficulty achieved in bouldering ($R^2 = 0.3396$, $t = 3.44$, $P = 0.0022$), hours of bouldering per week ($R^2 = 0.1721$, $t = 2.28$, $P = 0.0314$) and highest level achieved in sport climbing ($R^2 = 0.1371$, $t = 1.99$, $P = 0.0573$). Regression equations and plots for second moment of area data are given in Table 12 and Fig. 5. Results from analyses on total width and cross-sectional area are similar and are reported in Tables 13 and 14.

A partial correlation analysis was performed with the two significant variables, highest level of difficulty achieved in bouldering and hours of bouldering per

Table 7 PCA results for cross-sectional area data (climber/non-climber combined sample)

	Prin1	Prin2	Prin3	Prin4
Eigenvalue	13.83	2.03	1.18	1.07
(Proportion)	(0.5763)	(0.0849)	(0.0492)	(0.0446)
P-MC2	0.203287	0.075896	−0.222588	−0.119644
P-MC3	0.200528	−0.087930	−0.147223	−0.006059
P-MC4	0.190136	0.085066	−0.228467	0.188301
P-MC5	0.170514	0.119947	−0.305766	0.200525
P-PP2	0.199912	0.293315	0.105472	−0.090993
P-PP3	0.224180	0.207347	−0.017854	−0.131917
P-PP4	0.227315	0.253235	0.013039	−0.027726
P-PP5	0.178833	0.333669	0.055223	0.417951
P-MP2	0.198086	0.216358	0.208994	−0.354903
P-MP3	0.202535	0.210490	0.109481	−0.323947
P-MP4	0.219887	0.203471	0.077752	−0.124308
P-MP5	0.190316	0.281902	−0.072218	0.229672
L-PP2	0.225637	−0.092479	−0.111026	−0.088563
L-PP3	0.235839	−0.135376	−0.241443	−0.088784
L-PP4	0.230410	−0.192052	−0.209851	−0.040838
L-PP5	0.203387	−0.171011	−0.118362	0.412302
L-MP2	0.212491	−0.195528	−0.062119	−0.155708
L-MP3	0.215290	−0.302739	−0.020957	−0.129117
L-MP4	0.225065	−0.285478	−0.077503	−0.057064
L-MP5	0.197896	−0.164513	−0.014058	0.143859
L-DP2	0.180666	−0.119390	0.265963	−0.127697
L-DP3	0.182173	−0.274775	0.299324	−0.038741
L-DP4	0.176016	−0.162748	0.449142	0.263661
L-DP5	0.188197	−0.026716	0.447517	0.264895

P = posterior/anterior radiograph of right hand; L = lateral radiograph of left hand; MC = metacarpal; PP = proximal phalange; MP = middle phalange; DP = distal phalange; Number = Ray.

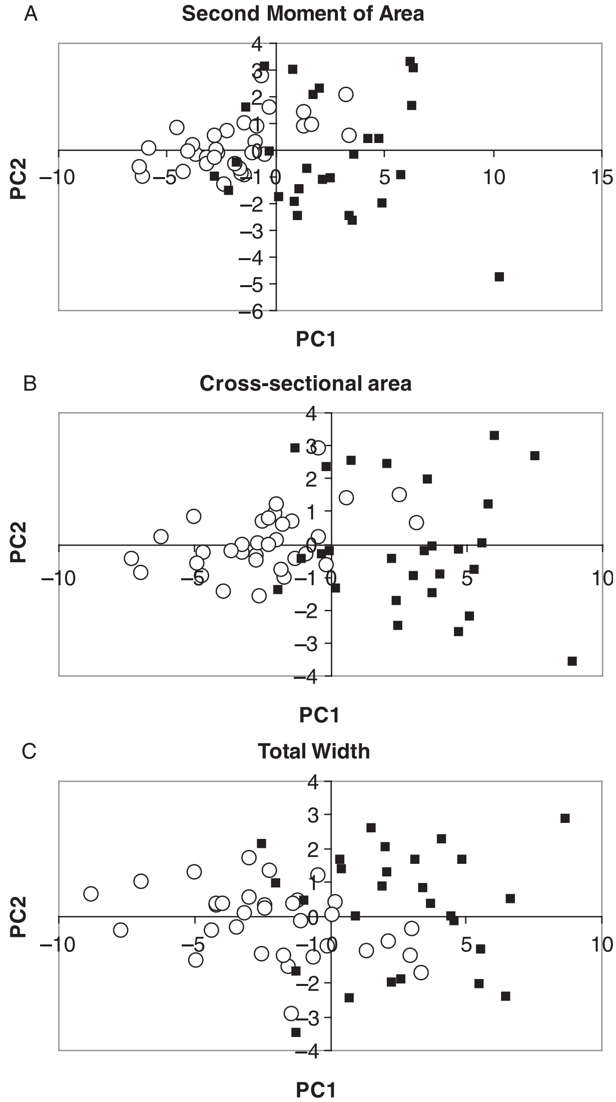

Fig. 4 First and second principal component from total sample PCA. Filled squares, climbers; empty circles, non-climbers.

week, and the first principal component of the second moment of area data. The partial Pearson correlation coefficient of hours of bouldering and the first principal component (after controlling for highest level achieved in bouldering) was 0.25 ($P = 0.24$). The partial Pearson correlation coefficient of the highest level of difficulty achieved in bouldering and the first principal (after controlling for hours of bouldering) was 0.43 ($P = 0.04$). Results were similar for the cross-sectional area data and for the total width data and are not reported.

A partial correlation analysis was also performed with highest levels achieved in bouldering, highest level achieved in sport climbing and the first principal component of the second moment of area data. The partial Pearson correlation coefficient of highest level of difficulty achieved in sport climbing and the first principal component (after controlling for highest level achieved in bouldering) was −0.003 ($P = 0.99$). The partial Pearson correlation coefficient of the highest level of difficulty achieved in bouldering and the first principal component (after controlling for highest level achieved in sport climbing) was 0.44 ($P = 0.03$). Results were similar for the cross-sectional area data and for the total width data and are not reported.

Discussion

Results from the OA analysis seem surprising in light of the known connection between joint stress and OA, as well as between age and OA. One explanation we considered is that the climbers who participated in this study may not climb at sufficient levels to incur the joint stress necessary to cause joint damage; however,

Table 8 PCA results for total width data (climber/non-climber combined sample)

	Prin1	Prin2	Prin3	Prin4	Prin5
Eigenvalue	13.50	2.00	1.56	1.13	1.02
(Proportion)	(0.5626)	(0.0835)	(0.0651)	(0.470)	(0.0424)
P-MC2	0.194305	−0.073646	−0.149610	0.172016	0.307678
P-MC3	0.195790	0.028541	−0.002293	0.223967	0.423745
P-MC4	0.186852	−0.045494	−0.020196	0.433016	0.340166
P-MC5	0.190610	−0.214738	−0.077098	0.231465	0.166280
P-PP2	0.207753	−0.293992	−0.022003	−0.113819	0.003911
P-PP3	0.225538	−0.218609	−0.097621	−0.143369	0.018319
P-PP4	0.229370	−0.286074	−0.079482	−0.014993	−0.013582
P-PP5	0.182534	−0.332482	0.065133	0.299805	−0.309380
P-MP2	0.200181	−0.176660	0.135723	−0.454575	0.058878
P-MP3	0.209155	−0.219776	0.109980	−0.303098	0.088618
P-MP4	0.223006	−0.206329	0.050809	−0.184657	−0.112638
P-MP5	0.197294	−0.177386	0.006710	0.115610	−0.256086
L-PP2	0.223820	0.123302	−0.169358	−0.102638	−0.137703
L-PP3	0.229913	0.176153	−0.236040	−0.072407	−0.107504
L-PP4	0.228106	0.219805	−0.229553	−0.045524	−0.092133
L-PP5	0.205674	0.174590	−0.122389	0.302095	−0.233798
L-MP2	0.221206	0.183447	−0.120836	−0.085873	0.094234
L-MP3	0.218915	0.260302	−0.053745	−0.166593	0.073844
L-MP4	0.216260	0.317278	−0.167520	−0.086519	−0.056975
L-MP5	0.215052	0.180495	−0.096927	0.031253	−0.140122
L-DP2	0.168847	0.123775	0.419059	−0.046695	0.260460
L-DP3	0.172327	0.254229	0.418137	−0.077230	0.212706
L-DP4	0.155403	0.150105	0.398347	0.140087	−0.324118
L-DP5	0.175259	0.057102	0.448771	0.170623	−0.218072

P = posterior/anterior radiograph of right hand; L = lateral radiograph of left hand; MC = metacarpal; PP = proximal phalange; MP = middle phalange; DP = distal phalange; Number = Ray.

Table 9 Results from ANOVA tests on first four principal components for the second moment of area data

	Climber		Non-climber			
	$\overline{X}$	SD	$\overline{X}$	SD	F	P
PC1	2.38	3.09	−1.95	2.37	37.92	< 0.0001
PC2	−0.23	2.10	0.17	0.93	0.91	0.3453
PC3	−0.02	1.53	0.02	0.97	0.02	0.8922
PC4	−0.27	1.48	0.22	0.71	2.95	0.0914

Table 10 Results from ANOVA tests on first four principal components for the cross-sectional area data

	Climber		Non-climber			
	$\overline{X}$	SD	$\overline{X}$	SD	F	P
PC1	3.00	2.78	−2.46	2.32	68.81	< 0.0001
PC2	−0.08	1.88	0.06	0.93	0.14	0.7073
PC3	0.02	1.31	−0.01	0.87	0.01	0.9128
PC4	−0.17	1.29	0.14	0.77	1.32	0.2547

the four climbers with the highest achieved levels of sport climbing and bouldering (5.13b–5.14b and V9–V12, which are considered elite levels of difficulty) had no indications of OA (scores of 0 for all joints). Another possibility is that the climbers in this study are simply too young to detect any changes consistent with OA; however, the climbers are on average older than the non-climbers.

Another possibility is that individuals with weaker hands or with OA-related difficulties may self-select themselves out of climbing. If an individual tries rock climbing and does not excel at it, or worse, experiences pain from it, they may decide to quit (or never take up) the sport. Those remaining long-term and at elite levels may be those who had healthier hands before beginning. The higher incidence of OA among the non-climbers, however, is most likely a spurious result of the sample.

Size accounts for the majority of sample variation: climbers have stronger fingers than non-climbers. The

Table 11 Results from ANOVA tests on first five principal components for the total width data

	Climber		Non-climber			
	$\overline{X}$	SD	$\overline{X}$	SD	*F*	*P*
PC1	2.53	2.84	−2.07	2.92	37.64	< 0.0001
PC2	0.23	1.77	−0.19	1.03	1.35	0.2508
PC3	−0.14	1.24	0.12	1.25	0.63	0.4289
PC4	−0.25	1.27	0.21	0.81	2.89	0.0947
PC5	−0.12	1.05	0.10	0.98	0.73	0.3949

Table 12 Results from regression analysis of first principal component (climbers only) on nine possible independent variables using second moment of area data

Variable	*n*	R^2	Intercept	Slope	*P*
Years	27	0.060	−1.099	0.146	0.216
Bouldering	25	0.340	−3.766	0.587	0.002
Sport	27	0.1371	−11.880	0.952	0.057
Traditional	18	0.006	−1.215	0.077	0.768
Hours hand training	27	0.670	−0.650	0.856	0.192
Hours bouldering	27	0.172	−0.900	0.228	0.031
Hours sport	27	0.030	−0.952	0.083	0.385
Hours traditional	27	0.045	−0.228	0.228	0.290
Hours gym	27	0.040	−0.954	0.254	0.319

eigenvectors associated with the first principal component for second moment of area, cross-sectional area and total width all have positive coefficients. Climbers have higher principal component scores than non-climbers, indicating that climbers have greater second moment of area, cross sectional area and total width for bones of the fingers and hands. The second principal component, for all three measures/variables, describes shape variation within the hand and fingers. Climbers and non-climbers are not significantly different along the second axis, indicating no major shape differences between groups. Subsequent components describe additional shape changes, although patterns are difficult to discern and no significant difference between groups exists.

Climbers have greater cross-sectional area than non-climbers, indicating that additional bone has been deposited to accommodate the mechanical stress associated with rock climbing. Analyses of total width and medullary width reveal that bone is being deposited on the subperiosteal surface, but not endosteally. These results conform to mechanical expectations. Increases in torsional and bending strength are made

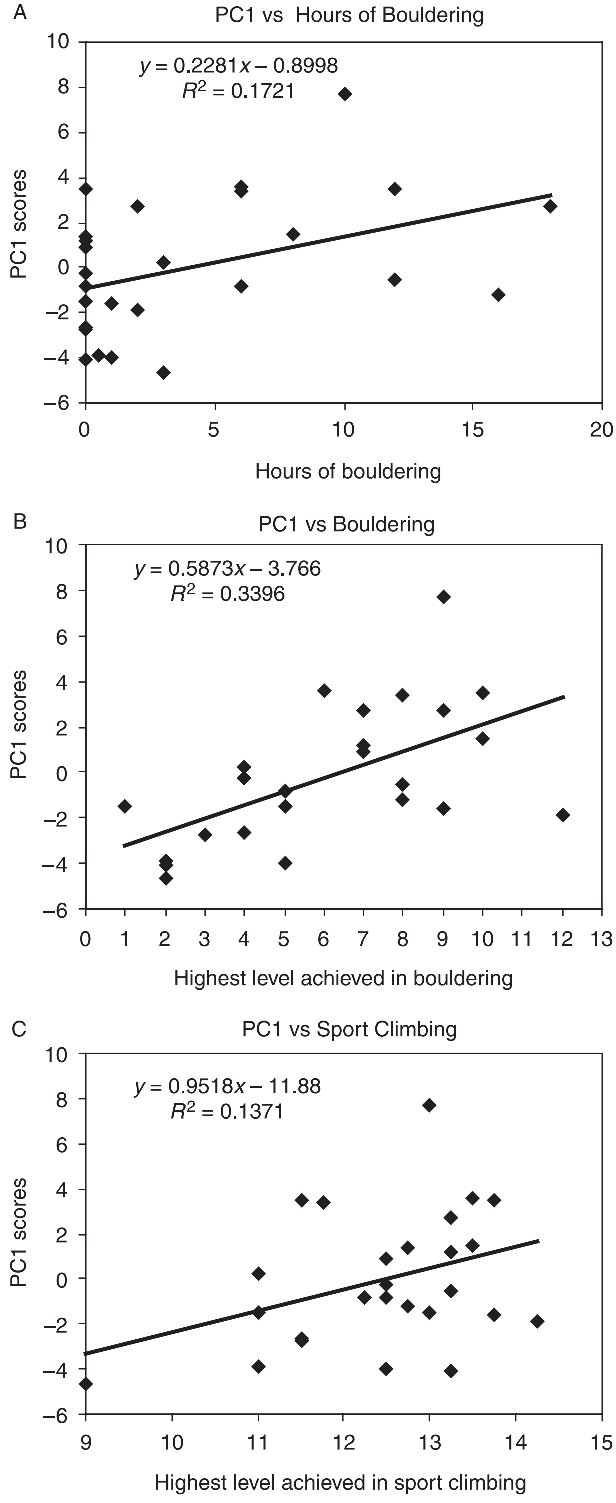

Fig. 5 PC1 scores from second moment of area data (climbers only) regressed on climbing-related variables.

by increasing second moment of area and polar moment of inertia, and these measures are greater in climbers. Because both measures are dependent not only on the cross-sectional area but also on how far

Table 13 Results from regression analysis of first principal component (climbers only) on nine possible independent variables using cross-sectional area data

Variable	n	R^2	Intercept	Slope	P
Years	27	0.062	−1.112	0.148	0.212
Bouldering	25	0.320	−3.698	0.572	0.003
Sport	27	0.157	−12.792	1.025	0.041
Traditional	18	0.015	−1.755	0.140	0.624
Hours hand training	27	0.108	−0.829	1.091	0.095
Hours Bouldering	27	0.168	−0.894	0.227	0.034
Hours sport	27	0.025	−0.862	0.075	0.435
Hours traditional	27	0.073	−0.294	0.294	0.172
Hours gym	27	0.103	−1.544	0.411	0.102

Table 14 Results from regression analysis of first principal component (climbers only) on nine possible independent variables using total width data

Variable	n	R^2	Intercept	Slope	P
Years	27	0.035	−0.873	0.116	0.352
Bouldering	25	0.375	−4.158	0.651	0.001
Sport	27	0.137	−12.469	0.999	0.057
Traditional	18	0.002	−0.035	−0.045	0.880
Hours hand train	27	0.032	−0.693	0.913	0.185
Hours bouldering	27	0.179	−0.963	0.244	0.028
Hours sport	27	0.018	−0.767	0.067	0.506
Hours traditional	27	0.042	−0.233	0.233	0.303
Hours gym	27	0.080	−1.418	0.377	0.153

that material is distributed from the neutral axis (the centre line of the bone cross-section), greater gains in strength are made if the same amount of material is added subperiosteally rather than endosteally.

One significantly complicating factor in comparing climbers and non-climbers, however, is the systemic response of bone to physical activity (Lieberman, 1996). Climbers may be a more active group than non-climbers and the increased cortical thickness may be part of a systemic response to that activity. The significant correlation of climbing ability with bone strength, however, suggests that the bone response is specific to climbing stress and not to overall activity level.

There does not appear to be a relationship between earlier initiation of climbing and thicker cortical bone. Most climbers (21 out of 27) in this study had finger and hand epiphyses that had fully fused (age > 16.5 years) when they began climbing, although the same number had probably not reached full skeletal maturity (age < 25 years). The age at which participants started climbing is not correlated with the first principal

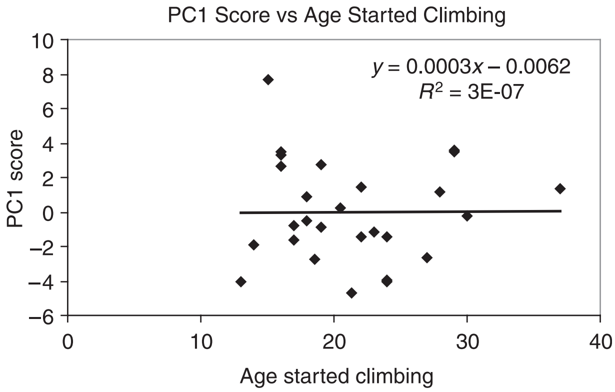

Fig. 6 PC1 scores from second moment of area data (climbers only) regressed on age at which participant started climbing.

component of the second moment of area data (Fig. 6). In fact, several climbers began climbing well after total skeletal maturity but their bones are among the strongest (Fig. 6). These results suggest that it is possible for adults to add bone subperiosteally in metacarpals and phalanges. Alternatively, climbers may be, as a group, generally more active over their lifetime, including prior to engaging in rock climbing. Thus, the fact that the climbers who began later in life have thicker hand and finger bones may reflect higher activity levels prior to skeletal maturity.

These results contradict the general findings that pre- and post-pubescent individuals add bone mainly on the endosteal surface (Bass et al. 2002). Optimization models suggest haversian remodelling to be dominant over modelling in distal segments to prevent additional energy expenditure resulting from accelerating additional mass in distal limb segments during motion (Lieberman et al. 2003). The additional mass in the hands and fingers is so small in relation to the whole limb that it possibly has little effect on energetic costs. These findings do support equilibrium models that predict bone changes that maintain stress strain ratios below a specific threshold (Frost, 1987).

Bouldering and sport climbing, in which physical/athletic difficulty is the primary emphasis, are important determinants of bone strength. Climbing difficulty is, at least partially, inversely related to the size of hand-holds and directly related to the degree of overhang. More difficult sport climbs and boulder problems are often considered more difficult because hand-holds are smaller and the rock face steeper. Steeper rock requires a greater proportion of the body mass to be supported by the hands and arms, while smaller holds decrease the area of the fingers over which body mass can be distributed. Both of these aspects produce greater stresses within the hands and fingers, and thus the relationship between higher climbing difficulty and bone strength is expected. Highest level in bouldering and sport climbing are probably similar measures of physical ability and encountered stress and we do not consider them to be independent predictors (Pearson correlation coefficient = 0.74).

Because bouldering involves short pieces of rock as compared with sport climbing, which generally involves cliffs of 40–100 feet, the average climbing movements on a bouldering route are more difficult than the average climbing movement on a sport climbing route of comparable difficulty. As a result, bouldering routes will have smaller hand-holds on steeper rock than sport climbing routes of comparable difficulty. Thus, bouldering is the style of climbing where participants are likely to generate peak levels of mechanical stress and is expected to have a greater effect. The significant correlation of highest difficulty level achieved in bouldering with measures of bone strength, after controlling for highest difficulty level achieved in sport climbing, supports this conclusion.

The hours of bouldering per week is a measure of the frequency of the maximal stress associated with bouldering. It may be that more frequent bouldering also leads to thicker cortical bone, but hours and highest achieved level of bouldering are mildly correlated (Pearson correlation coefficient = 0.55). The more a participant engages in bouldering, the more proficient they become and the more difficult routes they can attempt. The hours of bouldering, however, do not have a significant correlation with measures of bone strength after controlling for the highest level achieved in bouldering. The highest level of difficulty achieved in bouldering, by contrast, maintains a significant correlation with measures of bone strength after controlling for hours of bouldering. This suggests that the intensity of stress encountered is more important than the frequency of stress.

Conclusion

The results of this study suggest that the mechanical stress generated during rock climbing is sufficient to stimulate the bone deposition response. The relationship between measures of bone thickness and sport climbing and bouldering, and not traditional climbing or years of climbing, indicate that bone remodels to accommodate high-intensity mechanical stress and not to frequent low-intensity stresses, even if maintained over long periods of time. The results also suggest that it is possible for adults to deposit new bone subperiosteally, even if they have already reached skeletal maturity. The results do not support the findings from other studies that climbers have a higher incidence or earlier onset of OA.

Disclaimer

The research presented in this paper was not conducted under the auspices of the Federal Bureau of Investigation. The opinions expressed herein are those of the authors and do not reflect the US Department of Justice or the Federal Bureau of Investigation.

Acknowledgements

We would like to thank Cathy Graves for taking the radiographs, and Dr Gitta Lubke and Dr Richard Jantz for statistical assistance. We thank Dr Christopher Ruff for suggestions during the development of this work. We also thank the two anonymous reviewers for helpful comments and criticisms.

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