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Predicting metacarpal length using paired ratios with bilateral X-ray films

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Abstract

Introduction: When the metacarpal bones sustain severe osseous injury requiring reconstruction, functional recovery relies on the precise distribution of tension throughout full range of motion. While the small scale of hand structures compounds the effects of altering normal anatomy, literature lacks consensus recommendations for the acceptable degree of length alteration and/or appropriate methods of length estimation in reconstructive procedures. Length asymmetry has been reported in human metacarpal bones; however, studies assessing this phenomenon in living subjects with attention to functional implications or length prediction are lacking.

Methods: Hand X-rays were obtained for 34 patients aged 25–80 without history of metacarpal trauma, joint degeneration, or pathologic bone metabolism. A scaled bivariate model predicted metacarpal length using an ipsilateral paired metacarpal and matching contralateral ratio: Estimate_Dx_R = Median_Dy_R * (Median_Dx_L/Median_Dy_L). A second set of predictions used the contralateral metacarpal as a control. Pearson correlation coefficients, paired *t*-tests, and chi-square tests evaluated the symmetry between bilateral metacarpal lengths and paired metacarpal ratios as well as the accuracy of each predictive method.

Results: The contralateral control and target metacarpal differed significantly in digits 1, 2, 3, and 5. No significant difference in matched metacarpal ratios of the right and left hands was found. For all digits except 5D, bivariate model predictions generated were more strongly correlated with actual target length. Chi-square tests did not detect a significant difference in predictive value of the two models.

Conclusion: The scaled bivariate model we describe may be useful and economic in generating accurate length estimates of metacarpals for reconstructive procedures.

Keywords

Orthopedics/rehabilitation/occupational therapy, metacarpals, reconstruction, metacarpal length, metacarpal ratio, metacarpal asymmetry

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Introduction

Complex traumatic injuries of the hand structures must be properly reconstructed to restore normal function.[1] In cases of severe osseous metacarpal injury, functional recovery is dependent on the precise distribution of tendon tension throughout the full range of motion. Due to the scale of the bones in the hand, small changes in length have greater impacts on moment arms and tendon tension of the metacarpal joints. Accurate approximation of normal anatomy is crucial in these injury patterns, yet there are no consensus recommendations for generating length estimates to reconstruct metacarpal defects.

Direct contralateral measurements are often used to estimate metacarpal length. While these may be suitable controls for estimation of cross-sectional area, bone studies of the upper extremity have confirmed length asymmetry.[2,3]

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Table 1. Strict inclusion group demographic data.

n	34
Mean age (range)	49 (25–79)
Race/ethnicity	*n* (%)
White/Caucasian	27 (79.4)
Hispanic/Latino	4 (11.8)
Black/African American	3 (8.8)
Reason films initially obtained	*n* (%)
Neurological symptoms and/or pain	17 (50.0)
Trauma	13 (38.2)
Soft tissue abnormalities	4 (11.8)

Published reports indicate that the long bones of the right upper extremity are larger in all dimensions (including length, width, total volume, and cortical area), with a lesser degree of asymmetry shown in left-handed individuals.[1,4–7]

Further studies have confirmed bilateral metacarpal asymmetry in cortical thickness, cortical bone area, periosteal area, medullary area, percent cortical area, and the second moment of area in the mediolateral plane.[6,8–10] One study examining 65 adult skeletons obtained from a Medieval cemetery in Spain included bilateral length comparisons, as well as width measurements, in an attempt to identify sex, age, and handedness in modern human remains. Researchers found significant bilateral differences in lengths of the thumb/first digit (1D), second digit (2D), and fourth digit (4D) metacarpals.[11]

More recently, digit lengths have been considered as epidemiological predictors for variables including sex-hormone expression, reproductive success, spatial ability, physical prowess, and even disease disposition.[12–15] The authors found a single study examining bilateral proportional symmetry in 2D:4D metacarpal ratios in 3172 radiographs obtained as part of a large osteoarthritis genetic study.[14] Results showed no statistically significant difference between bilateral ratios. Multiple concerns appeared in this investigation such as patient selection methods and lax exclusion criteria which those authors confirmed interfered with data collection.

The majority of existing length ratio studies focus on sex differences.[12] It is well documented that males have a lower 2D:4D ratio compared to females.[12] However, the literature is limited in addressing the remaining digits. While metacarpal length asymmetry is established, no studies have evaluated proportional symmetry of the hand by examining each of the possible metacarpal length ratio pairs in a well-screened, heterogeneous population.[11]

Given that traumatic injury of the metacarpals is not limited to the second and fourth digits, we created a study to observe this effect in all metacarpal ratios of the human hand. We hypothesized that the metacarpals of the hand exhibit bilateral proportional symmetry such that the ratio of paired metacarpals is clinically indistinguishable from a matched ratio on the contralateral hand. By setting ratios equal to their contralateral equivalent, length estimates of pre-trauma bone length may be derived from paired relationships for use in surgical interventions. In what follows, we assess the asymmetry of bilateral metacarpals, the similarity of bilateral matched ratios, and the accuracy of a predictive model derived from left-right paired ratios.

Methods

Approval was obtained from our Institutional Review Board (IRB), and a total of 191 bilateral hand radiographs taken from 2010 to 2017 were collected for retrospective review. Preliminary analysis revealed a larger mean difference between left and right metacarpal length in our sample than was previously reported by Cashmore and Zakrzewski in their analysis of 65 adult skeletons.[11] At a statistical power level of 0.80 and an alpha of 0.05, this study required a minimum sample size of 26 patient films. Given that a smaller sample appeared sufficient to demonstrate asymmetry of individual metacarpals, we elected to divide our cohort into two groups.

To account for greater heterogeneity within our cohort and maintain statistical power, we elected to include all 34 patients who met the inclusion criteria for the "Strict Exclusion Group." These subjects met the following criteria: 25–79 years or age with no history of bone-associated neoplasms, osteolysis, osteoarthritis, trauma, or deviations from normal hand function in any of the metacarpals bilaterally. Strict Exclusion group demographic data is shown in Table 1.

In order to allow direct comparison with studies employing less strict inclusion criteria, we also collected data for all subjects without fractured metacarpals that were amenable to measurement, 175 subjects (34 from strict exclusion group + 141 additional subjects) were included in this "Expanded Group."

A non-observing experimenter randomized the films and divided them into right and left sets. This experimenter then presented the films to an observer who measured the metacarpals from digit 5 (5D) to digit 1 (1D) of the right hand to the nearest 0.01 mm for each patient. The films were then randomized a second time and, using the same methodology, the observer measured the metacarpals of the left hand. This process was repeated for three rounds of bilateral measurements, and the median length of each metacarpal was identified. Measurements were made from the midpoint of the metacarpal base to the midpoint of the apex using Cerner Skyview® (Cerner Corporation, Kansas City, Missouri, USA) (Figure 1). This measurement technique aligns with the existing literature and was confirmed by an additional radiologic consult.[10,14]

Contralateral length prediction model

Two metacarpal prediction matrices were then made for each digit. One prediction was generated using a scaled bivariate

Figure 1. X-ray film displays example measurement of the index (2D) and middle (3D) metacarpals used for ratio analysis.

model while the other used the matching contralateral metacarpal as a control estimate. To create the bivariate model, ipsilateral metacarpal ratios were set equal to the contralateral ratio: $\frac{Dx\_R}{Dy\_R} = \frac{Dx\_L}{Dy\_L}$. This relationship was then rearranged such that a target metacarpal length was estimated using an ipsilateral metacarpal length and the ratio of a matched length pair from the contralateral hand.

Statistical analysis

The student's paired two-tailed *t*-test was used to examine the direct relationship between the individual contralateral digits (i.e. first right metacarpal compared to the first left metacarpal) as well as between bilaterally matched metacarpal ratios. Each metacarpal was episodically paired with an ipsilateral metacarpal so that all digit combinations were achieved. Next, a matched pair ratio was generated for the contralateral hand. These arrays for the right and left hands were then analyzed using student's paired two-tailed *t*-tests to determine whether there was a significant difference in the paired metacarpal ratios between the right and left hands.

Next, logistic regression analysis was performed using both the bivariate model and the contralateral control methodology to compare their predictive accuracy. Pearson correlation coefficients were calculated to determine the strength of the relationship between each predictive method and actual measured length of the target metacarpal.

Chi-square tests were then performed to evaluate the accuracy of the scaled bivariate model versus a direct measurement of the contralateral metacarpal in predicting the length of the target metacarpal with an "accurate" result being within the parameter of 2 mm of the actual measured target length. A 2 mm cutoff was chosen with respect to the literature indicating that significant functional deficits emerge at this level.[16,17]

Results

Student's paired two-tailed *t*-tests within the exclusion group revealed that the contralateral control and the target metacarpal differed significantly in digits 1, 2, 3, and 5 (Table 2). In the fourth digit, however, the contralateral and target metacarpal lengths did not significantly differ. Student's paired two-tailed *t*-test in the expanded group showed statistically significant asymmetry in all digits except 1D.

In both the exclusion and expanded groups, student's paired two-tailed *t*-tests of matched metacarpal ratios of the right and left hands revealed no significant difference between the right and left ratios (Table 2).

Table 3 displays the Pearson correlation coefficients calculated between the actual metacarpal lengths and length predictions of the exclusion group. For all digits except the fifth digit (5D), predictions generated by the bivariate model were more strongly correlated with actual target length. The following target metacarpals are listed with their most accurate prediction ratio: 1D:2D for 1D, 2D:3D for both 2D and 3D, and 3D:4D for 4D. Compared to a direct contralateral measurement, bivariate model predictions (when using the most accurate paired ratio) were more often within 2 mm of the target metacarpal length in 1D-4D (Table 4). In 5D, the bivariate model and the contralateral measurement produced an equal number of misses. However, while the bivariate model had fewer misses in many of the combinations, chi-square-generated *p*-values were insufficient to establish significance (Table 5).

Discussion

No existing studies have described methodologies for predicting metacarpal length. In corrective surgical procedures of the hand, the contralateral metacarpal length is frequently used as a control though there is no consensus recommendation for using this method. This study has demonstrated that a bivariate model utilizing an ipsilateral metacarpal and a matched pair from the contralateral hand produces at least as accurate of predictions as a contralateral control method.

When treating metacarpal injuries, surgeons are often faced with decisions regarding the acceptable degree of metacarpal shortening, with guidelines in the literature ranging from 2 to 10 mm.[16] While it is well known that alterations of normal anatomy can alter functional outcomes, current literature has yet to elucidate clear mechanisms by which these

Table 2. Two-tailed paired *t*-test for contralateral metacarpal lengths and ratios are displayed for both exclusion and expanded groups.

Direct contralateral comparison	Exclusion group			Expansion group	
	Mean difference	*p*-values		Mean difference	*p*-values
1D	0.511	0.004	*1D*	0.205	0.059
2D	0.755	0.003	*2D*	0.386	0.006
3D	0.446	0.035	*3D*	0.280	0.024
4D	0.288	0.187	*4D*	0.277	0.013
5D	0.497	0.002	*5D*	0.405	0.001
Ratio					
1D:2D	0.000	0.901	*1D:2D*	0.000	0.891
1D:3D	0.003	0.285	*1D:3D*	0.001	0.750
1D:4D	0.005	0.135	*1D:4D*	0.000	0.927
1D:5D	0.001	0.682	*1D:5D*	–0.002	0.474
2D:3D	0.005	0.062	*2D:3D*	0.002	0.444
2D:4D	0.008	0.061	*2D:4D*	0.001	0.813
2D:5D	0.002	0.640	*2D:5D*	–0.003	0.479
3D:4D	0.002	0.512	*3D:4D*	–0.001	0.650
3D:5D	–0.004	0.389	*3D:5D*	–0.005	0.174
4D:5D	–0.005	0.144	*4D:5D*	–0.003	0.232

Table 3. Exclusion group—Pearson coefficients show the correlation between predicted and actual length of target metacarpals.

Pearson correlation coefficients						Control (contralateral metacarpal)
Target MC	Paired digit used for prediction ratios					
	1D	2D	3D	4D	5D	
Left 1D	–	0.968	0.963	0.967	0.967	0.962
Left 2D	0.957	–	0.982	0.967	0.955	0.957
Left 3D	0.945	0.981	–	0.977	0.966	0.964
Left 4D	0.941	0.959	0.972	–	0.964	0.945
Left 5D	0.945	0.955	0.966	0.968	–	0.969
Right 1D	–	0.963	0.956	0.958	0.959	0.962
Right 2D	0.968	–	0.981	0.962	0.954	0.957
Right 3D	0.959	0.981	–	0.973	0.965	0.964
Right 4D	0.956	0.959	0.972	–	0.963	0.945
Right 5D	0.960	0.953	0.965	0.965	–	0.969

All ratios were reported for the bivariate model.

functional impairments occur.[18] Proposed mechanisms include irregular tension of the metacarpal-traversing tendons and deviations in interossei muscle force generation.[16] In a 1995 cadaveric study, Low et al.[19] determined that a 3 mm reduction in metacarpal length was enough to cause significant deficits in flexion and extension force in the ring and long fingers. Another study reported a 7° extension tendon lag for every 2 mm of shortening.[17]

Changes in interosseous function have also been shown to affect performance of the entire hand. Damage to the ulnar nerve supplying the intrinsic muscles has been shown to decrease grip strength by 60%–90% and flexion force by as much as 88%.[16,20] Similar results might be observed following length changes in the metacarpals. When the metacarpal is translated proximally, the interosseous muscles lengthen, decreasing their maximum tension force.[16] A biomechanical study showed that metacarpal shortening of 2 mm resulted in 8% loss of interosseous power.[16] Given that intrinsic muscles have been reported to account for up to 60% of grip strength and 80% of pinch strength, it is imperative that surgeons accurately estimate patients' normal metacarpal length when considering possible treatment modalities.[21]

Prospective studies are needed to assess functional outcomes in patients who have undergone metacarpal injuries known to reduce length (e.g. spiral metacarpal fractures). We were able to find one study in the literature following 13 unoperated, non-scissoring spiral metacarpal fractures for grip strength outcomes.[22] While these patients did not have significant reductions in grip strength (compared to the uninjured contralateral hand), hand dominance was not accounted

Table 4. Exclusion group—instances of a "miss" by each model in predicting metacarpal length are shown.

Bivariate model versus contralateral measurement total misses (>2 mm)						Control (contralateral metacarpal)
Target MC	Paired digit used for prediction ratios					
	1D	2D	3D	4D	5D	
Left 1D	–	1	2	2	2	3
Left 2D	5	–	1	5	5	3
Left 3D	6	1	–	3	3	3
Left 4D	2	2	2	–	1	2
Left 5D	2	2	1	1	–	1
Right 1D	–	1	2	2	2	3
Right 2D	4	–	1	5	5	3
Right 3D	6	1	–	3	3	3
Right 4D	3	2	2	–	1	2
Right 5D	2	2	1	1	–	1

Misses were defined as >2 mm difference between predicted and actual length.

Table 5. Exclusion group—chi-square *p*-values are shown.

Target MC	Paired digit used for prediction				
	1	2	3	4	5
Left 1D	–	0.303	0.642	0.642	0.642
Left 2D	0.452	–	0.303	0.452	0.452
Left 3D	0.283	0.303	–	1.000	1.000
Left 4D	1.000	1.000	1.000	–	0.555
Left 5D	0.555	0.555	1.000	1.000	–
Right 1D	–	0.303	0.642	0.642	0.642
Right 2D	0.452	–	0.303	0.452	0.452
Right 3D	0.283	0.303	–	1.000	1.000
Right 4D	1.000	1.000	1.000	–	0.555
Right 5D	0.555	0.555	1.000	1.000	–

Misses were defined as >2 mm difference between predicted and actual length.

for and no attempt was made to estimate the degree of shortening. Future studies should cover a larger sample size and include additional functional outcomes such as total active range of motion and pinch strength.

Due to the retrospective nature of our study, the method for obtaining films was not standardized. As such, measurement landmarks were not clearly and consistently defined. This made measurement in certain films difficult, particularly in smaller metacarpals such as fourth and fifth digit. Future studies can improve upon our design by using a prospective methodology and standardizing film collection. Using an anterior-posterior film orientation with the hands laying on a flat surface would improve the visibility of the metacarpal bases, especially on the medial aspect of the hand. In addition, we had a wide variance in age, ethnicity, and gender for a small sample size and were not able to obtain information on hand dominance—a factor that is known to affect the degree of asymmetry.[6]

If prospective studies indicate that the bivariate model could be clinically useful, a prospective clinical trial in which patients are randomly assigned to surgical treatment groups using the bivariate model versus contralateral measurements with long-term outcomes is needed to directly assess the clinical implications of the model used in this study.

Our results align with the literature showing asymmetry in left-right metacarpal lengths.[6,8–11] *t*-tests demonstrated significant difference between matched contralateral metacarpals and target metacarpals in all digits but 4D in the exclusion group. Of note, the authors had the most difficulty identifying the midpoint of the metacarpal base in 4D and 5D which may have distorted these findings. Within the larger expanded group, only 1D lacked a significant difference. This expanded group included a large cohort of osteoarthritis patients. In these patients, the basal joint of metacarpal 1D is the most affected metacarpal joint and made identification of a consistent basal landmark challenging.[23]

After confirming length asymmetry, we then compared ratios of paired unilateral digits and found that proportions were not statistically different bilaterally. These findings further a study by Robertson et al.[14] which demonstrated left-right proportional symmetry in 2D:4D metacarpal ratio pairs. Robertson et al. restricted their analysis to a single metacarpal pair, sampled patients who were primarily limited to older-aged Caucasians, and included significant confounding comorbidities such as advanced joint degeneration or prior trauma to the hand. Their manuscript explicitly confirmed that bone shortening and deformity from arthritis/trauma interfered with metacarpal measurement. Our study evaluates all metacarpals in a racially heterogeneous population with a wide range of ages. Strict comorbidity exclusion criteria were also applied.

There are no existing studies evaluating the accuracy of metacarpal length predictions. Surgeons commonly use a contralateral metacarpal as a control estimate for predicting length in corrective procedures. Pearson correlation coefficients comparing our model to a contralateral measurement showed that the bivariate model produced measurements more strongly correlated with the target length in all digits except 5D.

Our study is limited by the small sample size and heterogeneity of our cohort. While results of chi-square analysis in our strict exclusion group did not show significant difference between the two predictive methods in all digits, we could not determine whether this was due to actual similarity or an insufficient sample size to distinguish between the two. Our parameters for an "accurate" estimation were derived from studies measuring maximum force production in cadaveric models. In practice, changes in normal anatomy are known to produce a compound effect on surrounding structures. When force generation of the interossei is altered, rotational malalignment becomes an additional concern. A malalignment greater than 5° can cause functional impairment.[16] Thus, it is possible that length alterations of >2 mm could significantly affect the functional status of patients.

Conclusion

The bivariate model presented in this study provides a simple and economic way to generate metacarpal length estimates that are at least equivalent to the current standard. Although we were unable to establish significantly improved accuracy using the bivariate model in all digits, there were no instances in which the bivariate model was outperformed by the contralateral control method. Given the trends in our data and the fact that current methods already require X-ray films, the authors recommend further studies be initiated to determine the clinical utility of this bivariate model in deciding appropriate metacarpal length.

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Declaration of conflicting interests

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Ethical approval

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Informed consent

Informed consent was not sought for the present study because none of the data used were identifiable, and our IRB waived the consent requirement for this retrospective study.

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