



Human thumb consists of three phalanges and lacks metacarpal? A morphometric study on the long bones of the hand

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Abstract

Purpose For many years, it was thought that the thumb consists of just two phalanges that differentiate it from the other four medial triphalangeal fingers. But there are some old reports that few former scientists believed the thumb has three phalanges and it lacked a metacarpal, and the thumb metacarpal is a phalanx. So this anthropometric study was carried out by investigating the morphology of the long bones of the hand and correlations between the thumb metacarpal and other miniature long bones of the hand.

Methods We studied anterior–posterior X-ray images of the right hands of 80 individuals from 18 to 65 years old. The exploration targets were the length of all metacarpals (MC), proximal phalanges (PP), middle phalanges (MP), and distal phalanges (DP). Friedman Repeated Measures Analysis of Variance and Dunn's post hoc test were carried out to compare the means of all variables. The correlation between all quantitative factors was done by Spearman Rank Correlation (Spearman's Rho) coefficient.

Results Our results showed that the length of the phalanges and the total length of the fingers are independent of the related metacarpal length ($P < 0.001$). Also, the thumb metacarpal length in comparison to all bones of the hand was significantly different from all long bones of the hand except the proximal phalanx of the middle finger ($P = 1$).

Conclusion Based on the morphology of the long bones of the hand and the high similarity between the thumb metacarpal and phalanges especially the proximal phalanx of the middle finger, it can be suggested that the current thumb metacarpal is a proximal phalanx of the thumb.

Keywords Hand evolution · Physical anthropology · Thumb · Metacarpal bone · Phalanges

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Abbreviations

DP	Distal phalanges
MC	Metacarpal
MP	Middle phalanges
PP	Proximal phalanges
TPT	Triphalangeal thumb

Introduction

Anthropometry, as a branch of physical anthropology, discusses the dimensions and sizes of the body, and also it is used in forensic medicine, brain and plastic surgeries, medical engineering, anthropomorphic robotic thumb designs [21], and even the clothing and eyewear industries [1, 9, 11].

The hand, as a grasping organ, is made up of the wrist joint, 8 carpal bones, 5 metacarpal bones, and the phalanges.

At the anatomical position, the digits include a lateral thumb with two phalanges and four fingers with three phalanges [13]. In all vertebrates except humans, the main function of the hand is locomotion, but bipedal locomotion in humans makes the hands free to do other works like holding, grasping, and lifting an object, so the hand's functions are different between vertebrates, and these changes in the functions lead to anatomic changes [6, 7].

Long thumb and shorter fingers in humans permit us to carry out precise movements with fingers and opposing the thumb to grasp objects [19]. One of the appropriate functional measures of thumb opposability and a proxy for manual dexterity is the thumb-to-digit ratio (intrinsic hand proportions or IHPs) which is used for comparing the hand proportions of humans with apes [4].

Galen reported that the thumb has three phalanges, and it lacked a metacarpal. Several years later, Vesalius in 1543, agreed with Galen and presented that the thumb metacarpal was really a phalanx. The mentioned findings were based just on the location of the secondary ossification center that is at the heads of the metacarpals of all fingers, while none is present in the thumb metacarpal head and also it is at the basis of the thumb metacarpal just like the location of the secondary ossification center of phalanges [10]. However, the hypotheses presented by the mentioned scientists were not particularly welcomed in recent centuries and nowadays all unanimously believe that the human thumb consists of two phalanges and a short metacarpal. On the other hand, the thumb is yet an important subject of the hand in many studies such as paleoanthropology, robotics, and molecular biology. Knowing the growth pattern of the thumb and especially its metacarpal may be a key for future studies.

Few studies have been conducted on this subject, so this anthropometric study was carried out by investigating the morphology of the long bones of the hand and correlations between the thumb metacarpal and other miniature long bones of the hand including phalanges and metacarpal bones using radiographic images.

Materials and methods

In this anthropometric study, we studied anterior–posterior X-ray images of the right hands of 80 individuals from 18 to 65 years old in Arak, Iran. Exclusion criteria were subjects who had any bone pathology or deformity in their hands. The maximum changes in phylogenesis and ontogenesis of the hand segments take place in childhood and it was demonstrated that these changes after 18 years are not significant [25]. The length between the X-ray source and the sensor and using the radiopaque ruler for confirming the accuracy of measurement were based on the Buryanov method [5]. The exploration targets were the length of all metacarpal

bones (MC1, MC2, MC3, MC4, and MC5) and proximal phalanges (PP1, PP2, PP3, PP4, and PP5), middle phalanges (MP2, MP3, MP4, and MP5) and distal phalanges of all fingers (DP1, DP2, DP3, DP4, and DP5) and the total length of four medial fingers by the sum of the length of three phalanges. Also, the length of all bony segments of each finger ray was calculated by the sum of the length of the phalanges and related metacarpal. All measurements were taken by one observer to avoid any bias.

Statistical analysis

All of the data were analyzed by Statistical Package for the Social Sciences software, version 22. For Descriptive statistics, we used mean \pm SD of the length of each bone. We required the Shapiro–Wilk test for assessing normality. Friedman Repeated Measures Analysis of Variance and Dunn's post hoc test were carried out to compare the means of all variables due to the lack of normality seen in most of variables. The correlation between all quantitative factors was done by Spearman Rank Correlation (Spearman's Rho) coefficient. Paired sample *t*-test was used to compare the means of two pairs of medial and lateral metacarpals of four medial metacarpals. $P < 0.05$ was considered as a statistically significant difference.

Results

Metacarpal bones

The average length of the MC1, MC2, MC3, MC4, and MC5 has been shown in Table 1 (Fig. 1). The longest was the second metacarpal bone, and the shortest was the thumb metacarpal bone. Between the four medial metacarpal bones, the fifth metacarpal bone was the shortest. The results of the present study showed a significant difference between

Table 1 The average length of miniature long bones of the hand for total subjects (Mean \pm SD) ($N = 80$)

Trait	MC	PP	MP	DP
Thumb (mm)	43.5 \pm 4.13	29.5 \pm 3.00	–	20.38 \pm 1.73
Index (mm)	65.8 \pm 6.13	38.1 \pm 3.70	21.35 \pm 1.86	15.1 \pm 1.16
Middle (mm)	61.2 \pm 5.75	42.37 \pm 4.50	25.85 \pm 2.25	16.31 \pm 1.83
Ring (mm)	53.83 \pm 5.16	39.76 \pm 4.28	24.52 \pm 2.31	16.21 \pm 1.82
Little (mm)	50.4 \pm 4.81	31.74 \pm 3.60	17.81 \pm 2.05	14.71 \pm 1.04

MC metacarpal, PP proximal phalanges, MP middle phalanges, DP distal phalange

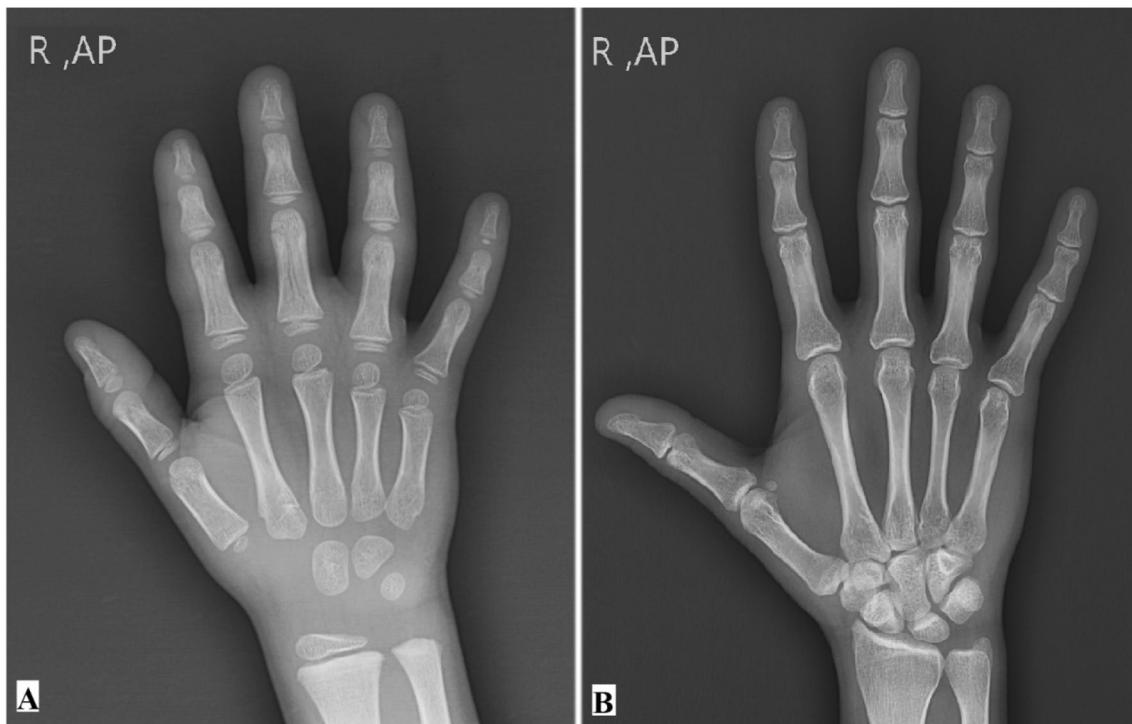


Fig. 1 Radiography of the hand. **A** Right hand of a 6-year-old boy. Note the difference between the ossification centers and regions ossified by primary and secondary centers of the miniature long bones of

the hand, especially the thumb. **B** Right hand of a 30-year-old man. All epiphyseal plates of the miniature long bones of the hand unite about age 18–20

the length of all metacarpal bones of the hand ($P < 0.001$) (Table 1). Also, there was a significant difference between the mean length of MC2 and MC3 as lateral metacarpals with the mean length of MC4 and MC5 as medial metacarpal bones ($P < 0.001$).

Phalanges

The mean lengths of all phalanges are highlighted in Table 1. The longest proximal phalanx in the hand belongs to the middle finger and then the ring, index, little finger, and thumb, respectively. The length order of middle and also distal phalanges in four medial fingers was the same as proximal phalanges. The proximal phalanx of the thumb was shorter than all other proximal phalanges, and its distal phalanx was longer than all other distal phalanges ($P < 0.001$). But the DP/PP ratio of the thumb in comparison to

different bony segments ratios was similar to DP/MP ratio in the index ($P = 0.38$) and ring ($P = 0.33$) fingers.

Thumb metacarpal bone

Analysis of the length of the first metacarpal bone and other miniature long bones of the hand, regardless of their ossification pattern, showed a significant difference between the thumb metacarpal and all phalanges and metacarpals of the four medial fingers except the proximal phalanx of the middle finger ($P = 1$). This finding indicates a high similarity between these two bony segments.

Fingers

To obtain the length of the four medial fingers, the total length of the three phalanges of each finger was calculated (Table 2, Fig. 2). There was a significant difference between the lengths of all four medial fingers ($P < 0.001$). The longest finger was

Table 2 The average of the finger length for total subjects (Mean \pm SD) ($N = 80$)

Trait	Thumb ^a	Index	Middle	Ring	Little
Finger length (PP + MP + DP) (mm)	49.85 \pm 2.34	74.47 \pm 4.98	84.54 \pm 6.73	80.51 \pm 6.63	64.27 \pm 5.85

^a Sum of the length of proximal and distal phalanges of the thumb (PP1 + DP1)

PP proximal phalanges, MP middle phalanges, DP distal phalange

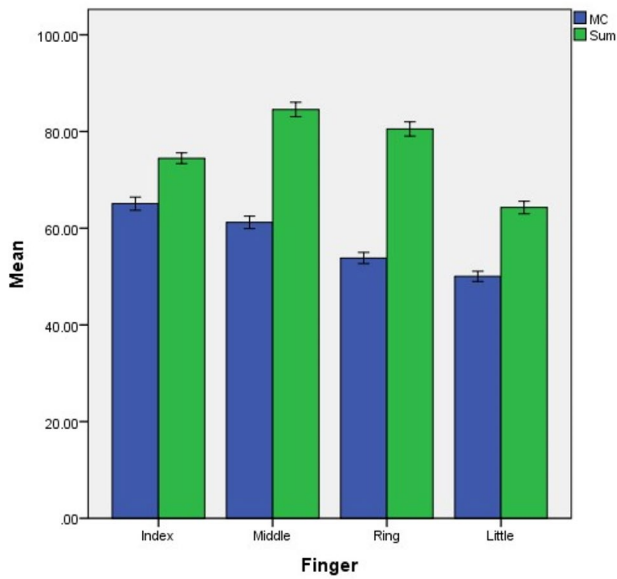


Fig. 2 The metacarpal length (blue) and the total finger length (green) of four fingers for 80 cases (mm)

the middle, and the shortest was the little finger. Statistically, a significant correlation was observed between the length of the distal phalanges of four medial fingers and the total finger length in all cases ($P < 0.001$). The average length of the ring finger was longer than the index finger ($P < 0.001$).

Finger ray length

Also, we calculated the sum of the length of each finger ray or metacarpal length plus related finger length. The longest was the sum of the middle finger and its metacarpal and then to the index, ring, and little finger, respectively ($P < 0.001$) (Table 3, Fig. 3). Based on our results, the mean Index/Ring finger length ratio was less than 1, but the Middle/Ring finger length ratio was greater than 1 (Table 4).

The sum of the length of all miniature long bones of the thumb (MC1 + PP1 + DP1) was calculated, and the mean length was 93.43 ± 8.12 mm. Also, the thumb to index ratio was 66%. Comparison of the sum of the length of these three bones of the thumb to four medial finger lengths showed that this sum was significantly longer than other fingers of

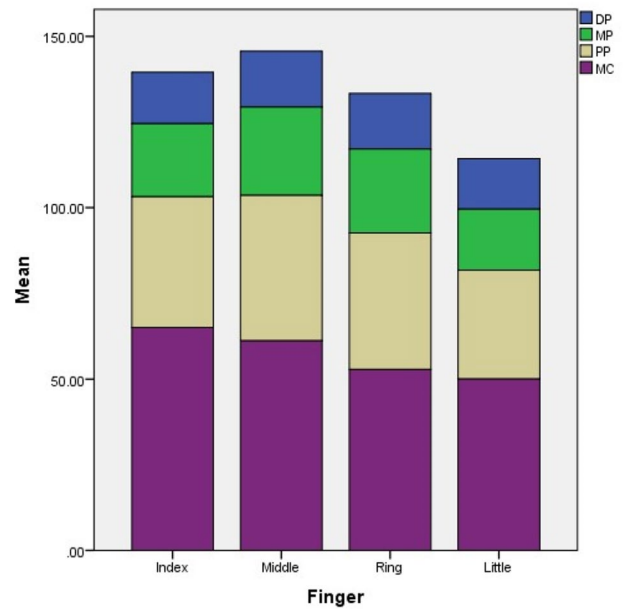


Fig. 3 The length of four bony components of fingers or finger ray length for 80 cases (mm)

the hand, even the longest finger or the middle finger ($P < 0.001$) (Tables 2, 3, Fig. 4).

Discussion

Based on the results of the present study, descriptive data of the morphometry of the individual bones were consistent with the results of similar studies on the anthropometric structure of the hand skeleton [5, 20]. For example, the Thumb/Index ratio was above 0.6, and Index/Ring ratio was less than 1, as some researchers reported previously [3, 14]. Our results showed that the length of the phalanges and the total length of the fingers are independent of the related metacarpal length. This means that the length order of the phalanges was different from the length order of the metacarpals. Also, the length order of the two phalanges of the thumb is not conforming to the phalangeal length order in four medial fingers. Although the distal phalanx of the thumb was longer than all distal phalanges in the hand, its adjacent phalanx which is known as the proximal phalanx

Table 3 The average length of the finger rays or length of the fingers plus related metacarpals for total subjects (Mean ± SD) (N=80)

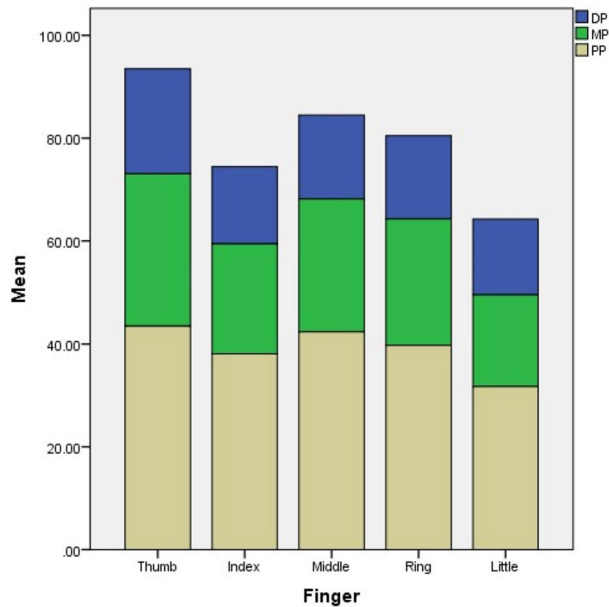
Trait	Thumb ^a	Index	Middle	Ring	Little
Sum of all bones related to a finger in the hand (MC + PP + MP + DP) (mm)	93.43 ± 8.12	139.55 ± 10.55	145.74 ± 11.85	134.34 ± 11.25	114.31 ± 10.25

^a Sum of the length of three long bones related to the thumb (MC1 + PP1 + DP1)

MC metacarpal, PP proximal phalanges, MP middle phalanges, DP distal phalanx

Table 4 The ratio between the length of some fingers for total subjects ($N=80$)

	Index/Ring	Middle/Ring	Little/Ring	Thumb/Index
Ratio	0.92	1.05	0.8	0.66

**Fig. 4** The sum of the length of three bony components of the thumb and four fingers for 80 cases (mm)

was the smallest proximal phalanx. But, at the same time, it was larger than all middle phalanges in the hand which implies be actually a middle phalanx based on the length order of the distal phalanges. Also, the thumb metacarpal length in comparison to all bones of the hand was interestingly similar to the proximal phalanx of the middle finger and these findings suggest that the metacarpal of the thumb may be actually a proximal phalanx.

Anatomy and morphology of the thumb metacarpal

The thumb metacarpal is thicker but shorter than other metacarpals. The head is less convex and is mildly flattened similar to the phalangeal heads. Also, the surfaces of the shaft differ from the other metacarpals and are similar to the shaft of the phalanges and consist of a concave palmar or medial surface instead of a sharp anterior border as seen in the other metacarpals. The base of the thumb is concavo-convex and forms a biaxial carpometacarpal or trapeziometacarpal joint rather than the other plane carpometacarpal joints [27].

Ossification of the miniature long bones of the hand

The thumb metacarpal ossifies similar to the phalanges and has two ossification centers, one of them is for the base of the metacarpal, and the other is for the body and the head. Other metacarpals also have two ossification centers, but the difference is that against the thumb and phalanges, one of the ossification centers forms the base and the body, and another is for the head at the distal end. At the 8th to 9th week of fetal life, ossification begins in the middle of the body, at first in the second and third metacarpals, and the last in the first metacarpal. The base of the thumb metacarpal and the heads of the other metacarpals begin to ossify in the third year, and in the twentieth year, they unite with the bodies of the metacarpals (Fig. 1) [27].

Anthropometric findings

Based on our results which were consistent with similar studies on the anthropometric structure of the hand skeleton, the longest metacarpal in the hand was the second metacarpal and then the third metacarpal. But the middle finger was the longest among the four medial fingers, followed by the fourth and then the index finger (Tables 1, 2, Fig. 2) [5, 20]. Comparing the length of the four inner metacarpals and the related fingers, it was found that the length of the finger and its longitudinal growth surprisingly are independent of the length of the metacarpals (Tables 1, 2, Fig. 2). The index finger that corresponds to the second metacarpal, which was the longest metacarpal in the palm, is the third finger in length among the four inner fingers and is shorter than the third and even fourth (or ring) finger, whose metacarpal is shorter than the second metacarpal. But adversely mentioned earlier, our analysis showed that the length of the three phalanges of each finger is correlated to the total finger length. So it can be suggested that the length of the fingers is independent of the length of the metacarpals.

The human thumb is usually evaluated as a different and unusual finger in many studies due to its differences in appearance, biomechanics, and different functions rather than other fingers. Various studies have been conducted to discover the relationship between molecular regulation of hand growth and its components and even hand geometry with health behavior and sexuality and even various disorders such as infertility [14, 23].

Littler demonstrated that the movement direction of digits follows an equiangular spiral and also the bone lengths follow the Fibonacci relationship [18] but in contrast, Andrew E. Park presented that just 1 of 12 bone length ratios contained the phi ratio [23]. The independent mechanism of the growth of the metacarpals and fingers that we showed may be the cause of this controversy in those studies. Based on our results, the length of the distal phalanx was significantly

correlated to the finger length in all fingers. On the other hand, the ring finger and also its distal phalanx is longer than the index finger and its distal phalanx, respectively. But Jung in 2015 by studying the fingernail configuration reported the order of the both length and width of the nails and also the width of the distal interphalangeal joints in four medial fingers belonging to the middle, index, ring, and finally little finger, respectively [15]. So both the length and width of the nail of the index finger are greater than the ring finger and are not accordant with the proven order of fingers length and distal phalanges [15]. The order reported by Jung is interestingly the same order as the sum of the length of all bones related to a digit (MC + PP + MP + DP) in the hand in this study (Table 3, Fig. 3). This can be the base of a hypothesis that the length and the width of the fingers are independent traits, but the width of the fingers and nail dimensions and total length of each finger ray including the metacarpal and three phalanges of each finger is controlled by common factors that need more investigations.

On the other hand, our results showed that the distal phalanx of the thumb was significantly longer than all the distal phalanges of the other fingers (Table 1). Jung also reported that the greater nail length, width, and width/length ratio in the hand belonged to the thumb. Although the distal phalanx of the thumb was the longest distal phalanx in the hand, its proximal phalanx was smaller

than other proximal phalanges, and this is an unjustifiable conflict because we showed the length of each phalanx in four medial fingers was related to the total finger length [15]. Also we showed that the DP/MP ratio in the thumb is similar to index and ring fingers. So it will be credible that the proximal phalanx of the thumb is actually a middle phalanx, and based on this, it is larger than other middle phalanges, similar to the order of distal phalanges length in hand.

As we mentioned earlier, our results showed that the thumb metacarpal was a unique bone similar to the proximal phalanx of the middle finger. If we assume the thumb metacarpal as a proximal phalanx and also the thumb as a three phalangeal finger, it will be the longest finger of the hand (Fig. 4) that this hypothesis is strengthened by Jung's results that showed the greatest dimensions of the nails and distal interphalangeal joints width in hand belong the thumb [15].

However, assuming this hypothesis, due to the absence of the fourth bony component in the thumb or a true metacarpal that would have been ossified similar to the other metacarpals, the total length of three bony segments of the thumb cannot be compared to the total length obtained from the sum of four bony segments in other fingers (Fig. 3). But it is conceivable that if a true metacarpal were formed proximal to the conventional and present thumb metacarpal, as seen in a few pathological specimens and hand anomalies

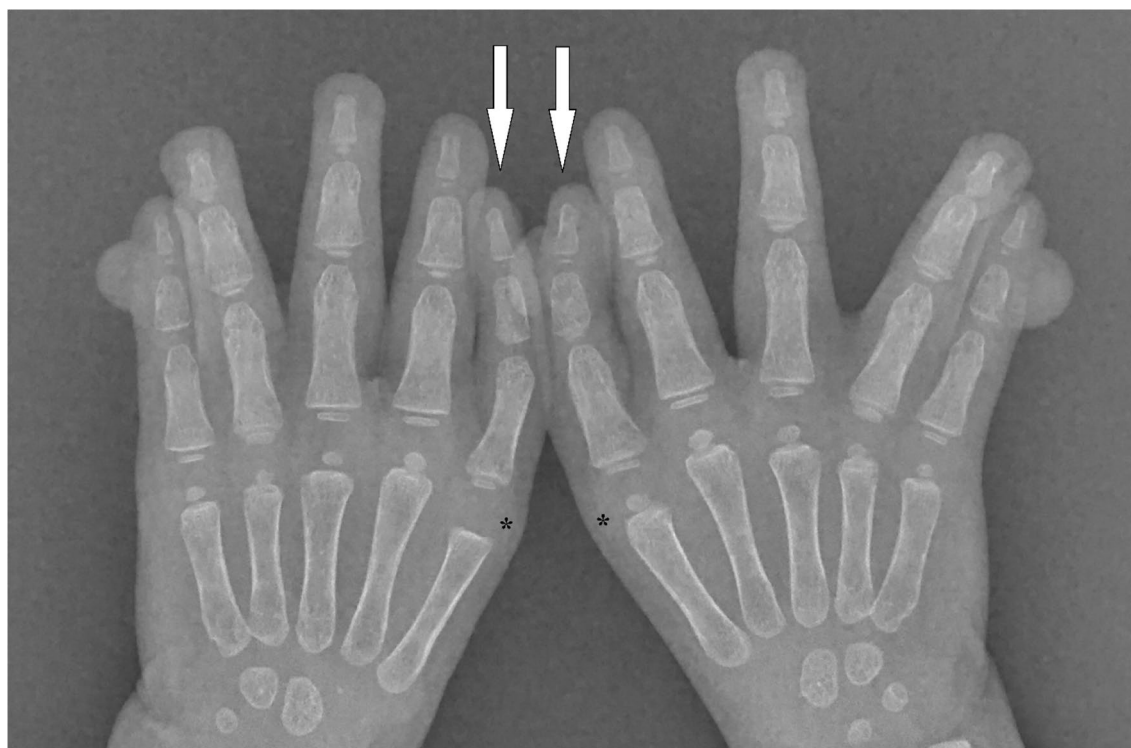


Fig. 5 Right and left hand with TPT. Note bilateral triphalangeal thumb (Arrows) and the form of ossification centers of atypical metacarpal thumb (*) [30]

known as the triphalangeal thumb (TPT) (Fig. 5), the sum of the four bony pieces would be larger than the sum of the length of the middle finger and its metacarpal. But in reality, this never occurs without any abnormal gene expressions. Therefore, it seems that the total length of the fingers plus metacarpals and the formation of the nails are regulated by common factors.

Triphalangeal thumb

If the thumb has a further phalanx, and a finger-like appearance, this inherent hand abnormality is called TPT and anticipated that it occurred at 1: 25,000 live births [30]. Clinical presentation of this anomaly can range extensively and may be found in both hands or unilateral. Previous studies proved that an entire duplication of the long-range Sonic hedgehog gene (Shh) regulator or mutations in ZRS is involved in the pathogenesis of TPT [30].

Metacarpal sign in Turner's syndrome

One of the deficiencies seen in Turner's syndrome is the "metacarpal sign" that medial metacarpals, especially the fourth and the fifth and related phalanges, form shorter than normal lengths [8]. We showed that the length of two inner metacarpals (fourth and fifth) and the two outer metacarpals (second and third) in pairs are very close. Although each later metacarpal from the ulnar side to the radial side was significantly longer than the former, there was a significant difference between the mean length of the sum of two inner or shortest metacarpals pair and two outer or longest pairs ($p < 0/001$). This finding can imply different growth patterns on the radial side of the hand. It should be noted that the second and third metacarpals begin to ossify almost simultaneously in the eighth or ninth week of the embryonic period [22].

A summary of the molecular regulation of hand evolution

The Sonic hedgehog gene (Shh) regulates the patterning and morphogenesis of extremities and is also involved in organogenesis. By expressing in the zone of polarizing activity (ZPA) on the medial border of the hand, Shh characterizes the anterior–posterior (radial–ulnar) axis of the limbs and thus guaranteeing the right number and morphogenesis of the digits [12].

From the ulnar side of the hand to the radial side, the length of metacarpals increases, and the longest is the second and the shortest is the fifth metacarpal. This indicates that, apart from Shh, whose incidence decreases toward the radial side, other factors may be related to genes playing role in determining the number and the length of the metacarpals

which suppresses Shh on the radial side of the hand plate. Also, Shh and BMPs seem to co-operate to form digits, and it has been suggested that the most anterior digit in the mouse limb is specified by BMPs, the next 3 digits by Shh and BMPs, and the most posterior digit by Shh alone [17]. BMP families are proved as key factors in programmed cell death between the fingers and may be the cause of this different and independent growth of the fingers and its related metacarpal [26].

Gli3 and Shh are two antagonistic factors realized that regulate the number of digits and are involved in failure, which is called polydactyly [28]. Gli3 appears to be mutually exclusive in limb buds and is believed to control Shh. In a null mutation of Gli3, Shh is additionally expressed on the radial side of the hand [24]. Also, GLI3 mutations are known to be associated with polydactyly [2]. These facts can explain different development of the radial side of the hand especially the thumb against the other fingers.

Biomechanics of the thumb

Also, the kinematics, size, and strength of the thumb's muscles are different in comparison with the other digits [16]. Also, biomechanical studies have shown that the middle finger is the strongest finger among the four medial fingers, and the thumb is more powerful than the four medial fingers [29]. This order of finger power seems according to Jung's results [15] about nail configuration and is rationally related to the nail dimension and following finger ray length including the sum of the metacarpal and phalanges length, not only to the finger length (Fig. 3). So common factors seem to determine the total length of a finger ray or the sum of the metacarpals and finger length and at the same time the muscle strength of each finger, especially the flexor muscles. On the other hand, the thumb is stronger than the middle finger (as the strongest and the longest finger ray among four inner fingers) in terms of muscle strength, but it lacks the fourth bony component or true metacarpal like the other fingers that it seems due to Shh suppression using some factors expressed on the radial side of the hand.

The results of this study showed that finger length growth is independent of metacarpal length growth. However, the total length of the four bony segments of each finger ray may be related to the strength of each finger, and this finding seems to be influenced by common factors with the evolution of the nail as well as its dimensions. Because the dimensions of the nail do not seem to be related to the length of the finger or the length of the metacarpal alone, it seems related to the total length of all these bony segments that need more investigation. On the other hand, our results showed that the length of the thumb metacarpal in addition to its morphology is similar to the length of the proximal phalanx of the middle finger compared to all similar bony pieces in the hand in which

the pattern of ossification is the same and can be named a proximal phalanx of the thumb. The ossification centers of the thumb metacarpal are like other phalanges and are different from the second to fifth metacarpals. The first metacarpal has a primary ossification center that forms the body and its head at the distal, and a secondary ossification center in the base at the proximal. Also, as discussed earlier, we can assume the present proximal phalanx of the thumb as a middle phalanx.

Therefore, according to the above and also regarding the difference in molecular regulation in the hand, especially on its radial side, the region where the thumb is located, it can be suggested that on the radial side of the palm due to the different gene expression and molecular modulation, the fourth bony component in the thumb or true first metacarpal is not formed. So the current metacarpal of the thumb may be called a proximal phalanx of the thumb but it needs more investigation to prove this hypothesis. Metacarpal ossification pattern in abnormal reported cases of triphalangeal thumb or TPT, which is similar to the ossification pattern of other normal metacarpals, is a very legitimizing morphologic reason for this hypothesis (Fig. 5).

Conclusion

Finally, we can conclude that the thumb metacarpal is morphologically similar to the proximal phalanx of the middle finger. So we suggest this hypothesis that the thumb metacarpal has been evolved in hominoids with three proximal, middle, and distal phalanges devoid of any metacarpal bone, as some zoologists and paleontologists believed in the 16th- and 17th-century and this hypothesis should be welcomed again although, it needs more studies to be confirmed.

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Author contribution SMJH: study concept and design, acquisition of data, analysis and interpretation of data, drafting of the manuscript. GRD: study concept and design, critical revision of the manuscript for important intellectual content, study supervision. BE: drafting of the manuscript, critical revision of the manuscript for important intellectual content, acquisition of data. MF: analysis and interpretation of data, critical revision of the manuscript for important intellectual content. SSBZ: acquisition of data, critical revision of the manuscript for important intellectual content.

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Declarations

Competing interests The authors declare no competing interests.

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