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Distraction Osteogenesis Outcomes in Hand Surgery: A Systematic Review and Meta-Analysis

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Abstract

Background: Distraction osteogenesis (DO) is a well-established technique for reconstructing congenital or acquired bone defects. This systematic review analyzed hand DO outcomes, quantifying length gain, complication rates, and correlations between technical parameters and clinical outcomes across anatomical (phalangeal vs. metacarpal) and etiological (traumatic vs. congenital) subgroups.

Methods: PubMed/MEDLINE, Embase, and Web of Science were searched through November 2024 for pre–post clinical studies. Data on length increase, distraction variables (rate, latency, consolidation), grip strength, range of motion, and complications were extracted.

Results: Thirty-eight studies including 433 patients (573 distractions) were analyzed. The pooled length increase was 19.8 mm (95% CI, 17.9–21.8), with slightly lower gains in patients <17 years (17.8 mm) versus ≥17 years (20.2 mm) and variations by bone type and etiology. Grip strength correlated negatively with distraction rate (r = –0.67) and positively with distraction time (r = 0.74), length increase (r = 0.72), and latency period (r = 1.00). Distraction rate also correlated positively with premature union (r = 0.56).

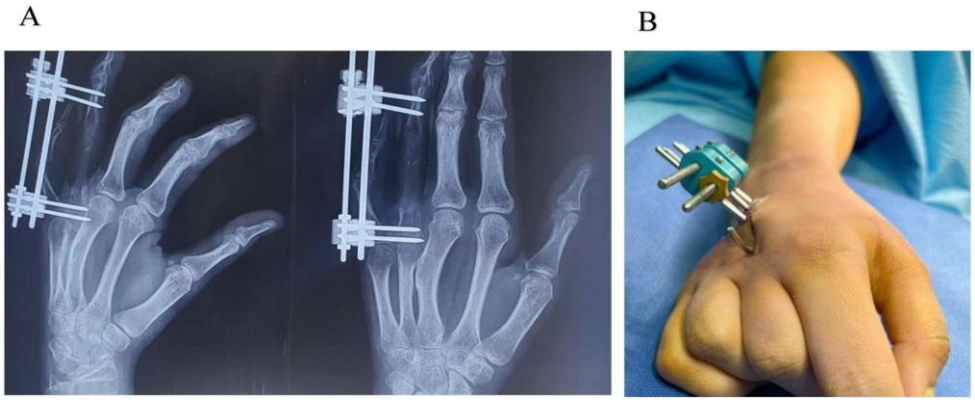
Conclusion: These findings indicate that hand DO reliably increases bone length, but outcomes and complications are influenced by patient age, bone type, and etiology.

Keywords

Distraction osteogenesis; Hand; Length increase Metacarpal; Phalanx.

Introduction

Distraction osteogenesis (DO) or callotasis is a well-known method for acquired and congenital bone defects reconstruction via lengthening, existing for more than a century [1]. It also has been proposed and described for hand surgery about 40 years ago [2]. This method is carried out via making an osteotomy followed by bone lengthening, slow distraction of healing fracture callus, and stabilization using an external fixator [3, 4] (**Figure 1**). DO surpasses traditional methods such as bone grafting, prosthetics, and vascularized flap procedures due to its superior outcomes including restoration of length and function with enhanced bone tissue quality, absence of donor site morbidity, sensation and vascularity maintenance, expedited reconstruction duration, and reduced post-treatment complications [5-10].



The DO procedure entails the osteotomy of a Bone Segment (BS) from intact bone tissue adjacent to the defect, maintaining its connection to surrounding soft tissue. Following this, the DO device is affixed to the bone, enabling gradual movement of the BS towards its intended position along a linear vector. Following installation, a latency phase spanning three to seven days ensues, during which the distractor remains inactive, allowing for bone tissue regeneration between the main bone and the osteotomized BS. Subsequently, the activation phase commences, wherein the BS is mobilized towards its destination by applying a Distraction Force (DF), facilitating expansion and regeneration of newly forming bone tissue to fill the generated gap. Upon completion of the activation phase and arrival of the BS at its destination, a consolidation phase follows, lasting between seven to ten days, during which the device remains inert, allowing for the consolidation of newly formed bone tissue. Ultimately, the treatment concludes with the surgical removal of the distractor [11-14].

While numerous case series in the literature explore distraction osteogenesis in hand surgery, there is a shortage of high-quality data guiding healthcare providers and patients.

Consequently, a consensus on the effectiveness, limitations, and complication rates of this procedure remains undefined. While Kempton et al. (2014) [15] established the baseline epidemiology of distraction osteogenesis in the hand, their review was limited to literature before 2012 and lacked an analysis of functional outcomes. Furthermore, their meta-analysis did not identify significant technical predictors for complications. Surgeons need to be acquainted with the expected outcomes and potential risks of distraction osteogenesis, comparing them with alternative methods like toe-to-hand transfers, to make informed decisions and effectively educate patients.

This systematic review and meta-analysis aimed to evaluate the 1) average length increase achieved with distraction osteogenesis in different bone types (phalangeal vs. metacarpal) and etiologies (traumatic vs. congenital) of hand shortening, and 2) to assess the associations between distraction-related technical variables (latency, active distraction, and consolidation phases) and complication rates across these subgroups in hand surgery studies.

Methods

Protocol

This systematic review and meta-analysis were conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis: the PRISMA Statement [16]. This review methodology was registered on the Open Science Framework (OSF) at https://osf.io/Knc54.

Search strategy

An electronic search was conducted in the databases PubMed/MEDLINE, Embase and ISI Web of Science from inception until November 20th, 2023. The search statement was: ((Distract) OR (Distraction) OR (distractor) OR (osteogenesis) OR (lengthening) OR (callostasis) OR (callotaxis) OR (callotasis)) AND ((Metacarpal) OR (Phalanx) OR (Phalangeal)). The references of retrieved articles were also checked to find possibly relevant studies. No filters were applied to limit the search results. Grey literature was not checked in this study.

Eligibility criteria and study selection

The present systematic review screened all studies that met the PICOD protocol requirements: P (Problem): metacarpal/phalangeal shortening; I (Intervention): distraction osteogenesis; C (Comparison): pre-operative length; O (Outcomes): post-operative length increase and complications rate; and D (design): pre-post clinical studies. All the search results were imported to Endnote X9 citation manager and duplicate studies were removed. Two reviewers (Removed Due to Blinding) independently screened the titles and abstracts of studies to select relevant ones. Disagreements were resolved by consensus.

All abstracts, review articles, case-reports, letters to editors, prototypes and animal studies were excluded. Whenever several studies were published from a trial with the same population, only the results and data of the last study (provided that it has the largest sample size, mentions accurate and complete information of patients in depth, and a complete/ correct reporting of the outcomes) would meet the criteria for our systematic review. A PRISMA flow diagram of the screening process in presented in (**Figure 2**).

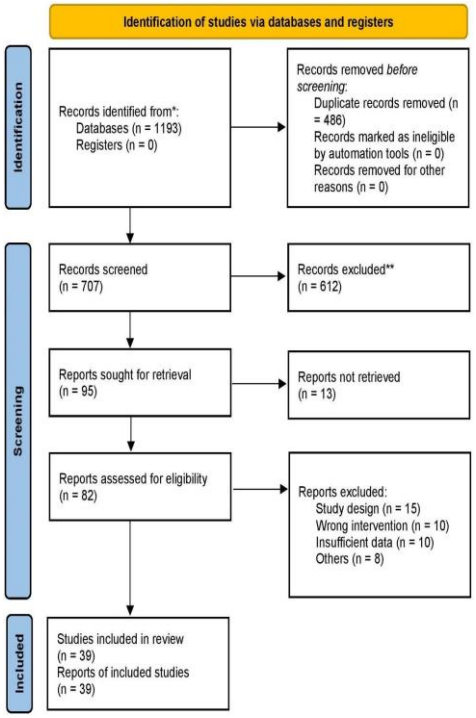


Figure 2: PRISMA flowchart of the systematic review process.

Data extraction

Two reviewers separately collected data from full texts of included studies using a pre-designed Excel form. Results were compared and double checked by the same reviewers. The data extracted included: author, year, study design, sample size, mean age, sex ratio, distracted bone (phalanx or metacarpus), shortening cause (trauma or congenital), pre and post distraction length, latency period duration, active distraction time, consolidation time, distraction rate, and healing index (the time needed for external fixation to provide 1 cm of lengthening (days/cm)). Furthermore, the outcomes' data of grip and pinch strength, range of motion (ROM), and complications rate like infection, fracture, subluxation, and angulation were extracted.

Quality assessment

The methodological quality and validity of each included study was evaluated using the Quality Assessment Tool for Before–After Studies with no Control Group for clinical trials and single group studies (**Table 1**), as recommended by the National Institutes of Health (NIH). This tool evaluates studies across 12 distinct domains to determine internal validity and risk of bias. The domains include: (1) clarity of study question; (2) eligibility criteria; (3) representativeness of the study population; (4) enrollment of all eligible participants; (5) justification of sample size; (6) description of the intervention; (7) clarity of outcome measures; (8) blinding of outcome assessors; (9) loss to follow-up; (10) statistical methods; (11) multiple outcome measurements; and (12) group-level interventions.

Two independent reviewers screened the full-text articles and assigned a quality rating to each study. Scoring was based on the cumulative number of "Yes" responses to the criteria, resulting in a final quality

score for each study. Discrepancies were resolved through discussion and consensus.

Statistical analysis

Our primary outcome was length increase. Secondary outcomes included distraction osteogenesis technical variables (latency period, active distraction time, consolidation time, distraction rate) and clinical outcomes, including grip strength and complication rates. The increase in length and the technical measures (distraction rate, distraction time, consolidation time, latency period) were reported as mean difference (±standard deviation) and mean (±standard deviation), respectively.

Forest plots were generated to assess heterogeneity and calculate the pooled weighted mean difference (WMD) for length increase with corresponding 95% confidence intervals (CIs) for visual inspection across studies. All statistical tests were two-tailed, and the significance level was set at less than 0.05 for all, except for the heterogeneity test. Statistical analyses were performed using Stata version 17.0 (Stata Corp., College Station, Texas, USA). Heterogeneity among the included studies was assessed using the I2 statistic and Chi-square test (P value). Given the anticipated variability in clinical protocols and patient populations, a random-effects model was employed for all meta-analyses to provide a conservative estimate of the pooled effect.

For correlational analysis, cases were divided into six subgroups based on age, bone type, and etiology of shortening. Pearson's correlation coefficient was used to examine relationships between technical variables and functional outcomes or complications. Technical variables included consolidation time (days), distraction rate (mm/day), distraction time (days), and latency period (days). Outcome variables included length increase (mm), postoperative grip strength (percentage of the contralateral side), and range of motion (degrees) of the meta carp phalangeal joint (flexion and extension). Complication rates, including premature union, non-union, infection, angulation, instability, and dislocation, were also assessed.

Results

Data extraction (Descriptive results)

A total of 39 studies published between 1980 and 2023 were included in this review, including 433 patients (573 distractions). The sample sizes across the included studies varied significantly, ranging from small cohorts of 2 patients to larger series including up to 65 15patients. The age of participants spanned a wide spectrum, covering both pediatric and adult populations; reported mean ages ranged from as young as 3.9 years in congenital cases to 42.8 years in adult trauma cohorts. Gender distribution was generally mixed, though some studies showed a male predominance, particularly in trauma-related cohorts. The etiology of the bone defects or shortening was primarily categorized into traumatic amputation or loss [17] [18] and congenital anomalies [19, 20], with several studies including a mix of both indications (**Table 1**).

N	Study (year)	Country	Design	Sample size (patient)	Sample size (distraction)	Bone	Graft	Cause (trauma/congenital)	F/U (mean months)	Age (mean (range))	Gender (m/f ratio)
1	Arata (2011)	Japan	Retrospective	8	10	MC: 5 P: 5	No	2-Jun	21.8 (6-36)	33.75 ± 18.79	5-Mar
2	Arslan (2001)	Turkey	Prospective Pre-post	6	6	MC	No	2-Apr	19 (12-28)	12 (10-14)	4-Feb
3	Baccari (2006)	Tunisia	Prospective Pre-post	12	12	MC: 8 P: 4	3	Dec-00	Feb-96	30 (13-50)	5-Jul
4	Bashour (2023)	USA	Case-series	4	5	MC	1	1-Apr	NA	18 ± 10.95	NA
5	Bodmer (2017)	Switzerland	Prospective Pre-post	5	5	P	No	May-00	16.8 (4-44)	39 (24 - 53)	May-00
6	Bosch (2004)	Spain	Prospective Pre-post	18	18	MC	12	18/0	36-108	38 (18-56)	16/2
7	Bozan (2006)	Turkey	Retrospective	8	18	MC	No	0 / 18	23.6	18.6 ± 6.5	0/8
8	Bulut (2013)	Turkey	Prospective Pre-post	4	7	MC	No	0/7	34.57 (26 - 37)	14.9 (13-18)	3-Jan
9	Cansu (2015)	Turkey	Retrospective	14	14	P	No	14 / 0	84 (12–144) days	27 (18–43)	13/1
10	Dana (2017)	France	Retrospective	7	7	MC	No	6-Jan	> 12	NA	NA
11	Das (2009)	India	Prospective Pre-post	9	9	MC: 5 P: 4	2	4-May	24 - 48	20.11 (18-23)	3-Jun
12	Dhalla (2001)	USA	Prospective Pre-post	16	27	MC: 20 P: 7	1	25-Feb	35 (10-71)	7.9 (2 - 16)	NA
13	Erdem (2009)	Turkey	Prospective Pre-post	7	12	MC	No	0/6	57.5 (12 - 96)	14.5 (10-21)	13-Feb

Table 1: The included studies' descriptive data.

The distraction protocols employed across the studies showed relative consistency in rate but variation in timing. The latency period, the time between osteotomy and the start of distraction, most frequently ranged between 5 and 7 days, though extremes were observed, such as 0 days in Ogino (1994) [21] and up to 14 days in Finsen (1996) [22]. The rate of distraction typically ranged from 0.25 mm/day to 1.0

mm/day, with 0.5 mm/day and 1.0 mm/day being the most common specific increments reported. Fixation and consolidation periods varied widely depending on the length of distraction required, with mean fixation times exceeding 100 days in several studies, such as Kanchanathepsak (2020 [23]) and Matev (1980) [24] (**Table 2**).

N	Study (year)	Latency period (days)	Distraction rate (mm/day)	Distraction Time (days) (mean)	Consolidation Time (days)(mean)	Fixation Time (days) (mean)	Initial length Mean (mm)	Final Length Mean(mm)	Length increase (mm)	Length increase (%)
1	Arata (2011)	NA	1	35.8 ± 6.18	NA	88.9 ± 18.22	NA	NA	13.7 ± 2.79	NA
2	Arslan (2001)	6	0.5	37 (32 - 44)	48.75	85.75 (80.5-105)	NA	NA	18.5 (16-22)	NA
			0.25 (9)/							63.3 (33.2 -
3	Baccari (2006)	6.41	1 (2)/ 0.5	150 (30-330)	120 (90-180)	124.6 (30 - 330)	NA	NA	26 (15 - 34)	82.5)
			-1							
		6.6 ±	0.902 ±		77 ± 21.21					
4	Bashour (2023)	0.5 5	0.1	21 ± 3.29	-4	100.25 ± 26.40	NA	NA	1.25 ± 0.31 (4)	NA
5	Bodmer (2017)	7	0.65	96 (70 - 125)	15 (7 - 28) W	NA	NA	NA	26.2 (23 - 30)	NA
6	Bosch (2004)	7	0.2-0.4	204 (75 - 420)	NA	NA	NA	NA	31 (20-40)	NA
7	Bozan (2006)	5	0.5	40.2 ± 7.3	82 ± 23.1	122. 3 ± 27.9	29.9 ± 2.4	NA	16.5 ± 2.7	54.6 ± 10.2
			0.55 (0.48 -				34.57 (33			44.18 (41.6 -
8	Bulut (2013)	7	0.63)	27.71 (24 - 35)	57.1 (54 - 64)	70.14 (70 - 99)	- 37)	NA	15.14 (14 - 17)	51.5)
9	Cansu (2015)	10	1	NA	NA	85 (72-113)	29	49	20 (17-26)	168
10	Dana (2017)	NA	0.3 (0.1 - 0.5)	NA	NA	100 (60-155)	NA	NA	13 (8-21)	38

Table-2: Included studies' variables description.

The distraction protocols employed across the studies showed relative consistency in rate but variation in timing. The latency period, the time between osteotomy and the start of distraction, most frequently ranged between 5 and 7 days, though extremes were observed, such as 0 days in Ogino (1994) [21] and up to 14 days in Finsen (1996) [22]. The rate of distraction typically ranged from 0.25 mm/day to 1.0 mm/day, with 0.5 mm/day and 1.0 mm/day being the most common specific increments reported. Fixation and consolidation periods varied widely depending on the length of distraction required, with mean fixation times exceeding 100 days in several studies, such as Kanchanathepsak (2020 [23]) and Matev (1980) [24] (**Table 2**)

Quality Assessment

A total of 39 studies were evaluated for methodological quality. The quality assessment scores ranged from a minimum of 6 to a maximum of 10, with a mean score of 8.2, indicating a generally moderate-to-good quality across the included literature. Only two studies, Pensler (1998) and Seitz (1991), received the lowest score of 6. The vast majority of studies failed to provide a sample size justification or power analysis. Only a single study (Das, 2009) met the criteria for this domain, scoring a "Yes," (**Table 3**).

ID	Author (Year)	1	2	3	4	5	6	7	8	9	10	11	12	Quality Rating
1	Arata (2011)	Yes	Yes	Yes	Yes	No	Yes	Yes	NA	Yes	No	No	NA	9
2	Arslan (2001)	Yes	Yes	Yes	NA	No	Yes	Yes	NA	NA	No	No	NA	9
3	Baccari (2006)	Yes	No	NA	NA	No	Yes	Yes	No	NA	No	No	NA	7
4	Bashour (2023)	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	NA	8
5	Bodmer (2017)	Yes	Yes	Yes	NA	No	Yes	Yes	NA	NA	No	No	NA	9
6	Bosch (2004)	Yes	Yes	Yes	NA	No	Yes	Yes	No	NA	No	No	NA	8
7	Bozan (2006)	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	NA	9
8	Bulut (2013)	Yes	Yes	Yes	Yes	No	Yes	Yes	No	NA	Yes	No	NA	9
9	Cansu (2015)	Yes	Yes	Yes	NA	No	Yes	Yes	NA	NA	No	No	NA	9
10	Dana (2017)	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	NA	8
11	Das (2009)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA	Yes	No	NA	10
12	Dhalla (2001)	Yes	Yes	Yes	NA	No	Yes	Yes	No	NA	No	No	NA	8
13	Erdem (2009)	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	NA	9
14	Fang (2021)	Yes	Yes	Yes	NA	No	Yes	Yes	No	NA	Yes	No	NA	9
15	Finsen (1996)	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	No	No	NA	7
16	Heitmann (2004)	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	NA	9
17	Heo (2008)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA	Yes	No	NA	10
18	Hosny (2012)	Yes	Yes	NA	NA	No	Yes	Yes	No	NA	Yes	No	NA	9
19	Houshian (2001)	Yes	Yes	Yes	NA	No	Yes	Yes	No	NA	No	No	NA	8
20	Iba (2021)	Yes	Yes	Yes	NA	No	Yes	Yes	No	NA	No	No	NA	8
21	Kanchanathepsak -2020	Yes	Yes	Yes	NA	No	Yes	Yes	No	Yes	Yes	No	NA	9
22	Kato (2002)	Yes	Yes	Yes	NA	No	Yes	Yes	No	Yes	No	No	NA	8
23	Komurcu (2008)	Yes	Yes	No	NA	No	Yes	Yes	No	NA	No	No	NA	7
24	Lam (2019)	Yes	Yes	No	NA	No	Yes	Yes	No	No	Yes	No	NA	7
25	Matev (1980)	Yes	No	Yes	NA	No	Yes	Yes	No	NA	No	No	NA	7
26	Matsuno (2004)	Yes	Yes	Yes	NA	No	Yes	Yes	No	NA	Yes	No	NA	9
27	Ogino (1994)	Yes	No	Yes	NA	No	Yes	Yes	No	NA	No	No	NA	7
28	Parmaksizoğlu	Yes	No	Yes	NA	No	Yes	Yes	No	Yes	No	No	NA	7

	-2004													
29	Pensler (1998)	Yes	No	NA	NA	No	Yes	No	No	NA	No	No	NA	6
30	Rösslein (1993)	Yes	No	Yes	NA	No	Yes	Yes	NA	Yes	No	No	NA	8
31	Saleem (2019)	Yes	Yes	Yes	NA	No	Yes	Yes	No	Yes	Yes	No	NA	9
32	Sawaizumi -2003	Yes	No	Yes	NA	No	Yes	Yes	No	NA	No	No	NA	7
33	Seitz (1991)	Yes	No	Yes	NA	No	Yes	No	No	Yes	No	No	NA	6
34	Sen (2003)	Yes	No	Yes	NA	No	Yes	Yes	NA	Yes	No	No	NA	8
35	Toh (2002)	Yes	Yes	Yes	Yes	No	Yes	Yes	No	NA	Yes	No	NA	9
36	Valenti (2006)	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	NA	7
37	Vekris (2015)	Yes	Yes	Yes	Yes	No	Yes	Yes	NA	Yes	Yes	No	NA	10
38	Wang (2018)	Yes	Yes	Yes	Yes	No	Yes	Yes	NA	Yes	No	No	NA	9
39	Zimmermann -2003	Yes	Yes	Yes	Yes	No	Yes	Yes	NA	Yes	No	No	NA	9

Table 3: Methodological Quality of the Included Studies Using the Quality Assessment Tool for Before-After Studies with No Control Group.

Meta-analysis

The pooled mean difference between pre- and postoperative length was 19.81 mm (95% CI: 17.87, 21.75) **(Figure 3).** Heterogeneity across studies was high (I^2 > 95%). Subgroup analyses were performed by age, bone type, and etiology **(Table 4).** Patients under 17 years had a pooled length increase of 17.84 mm (95% CI: 15.24, 20.44) with heterogeneity of I^2 = 93.1% **(Figure S1).** Patients aged 17 years or older had a pooled increase of 20.22 mm (95% CI: 16.85, 23.59) with I^2 = 98% **(Figure S2).** In congenital metacarpal cases, length increased by 17.40 mm (95% CI: 16.09, 18.71, I^2 = 72.1%) **(Figure S3).** Traumatic metacarpal cases increased by 22.74 mm (95% CI: 19.81, 25.67, I^2 = 92.5%) **(Figure S4).** Congenital phalangeal cases increased by 25.38 mm (95% CI: 22.76, 28.00, I^2 = 50.1%) **(Figure S5).** Traumatic phalangeal cases increased by 18.22 mm (95% CI: 13.97, 22.47, I^2 = 97.7%) (**Figure S6**). Funnel plots suggested no evidence of publication bias.

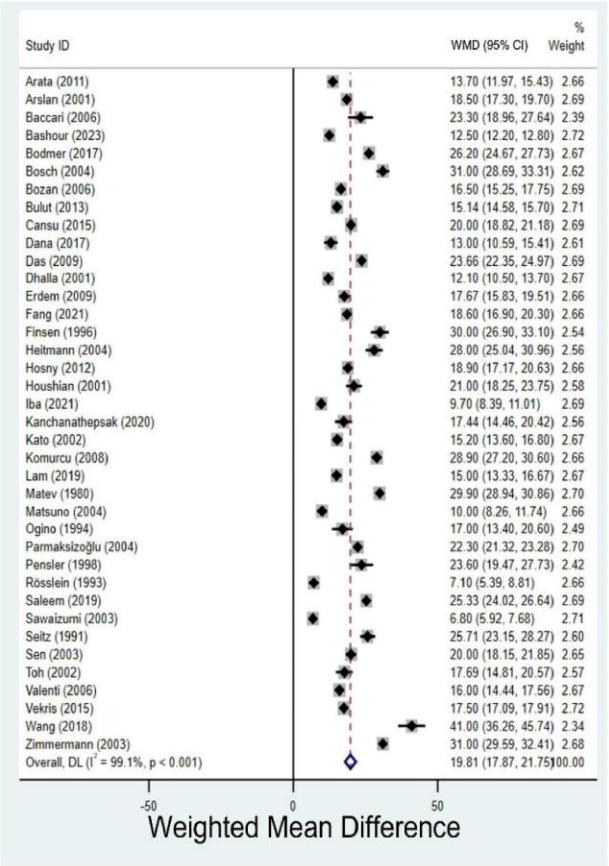


Figure 3: Forest plot showing the increase in limb length (mm) in patients following distraction osteogenesis.

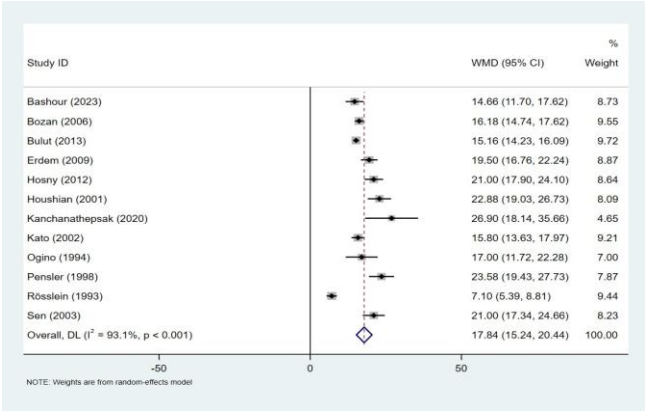


Figure S1: Forest plot of length increase (mm) in patients under 17 years of age.

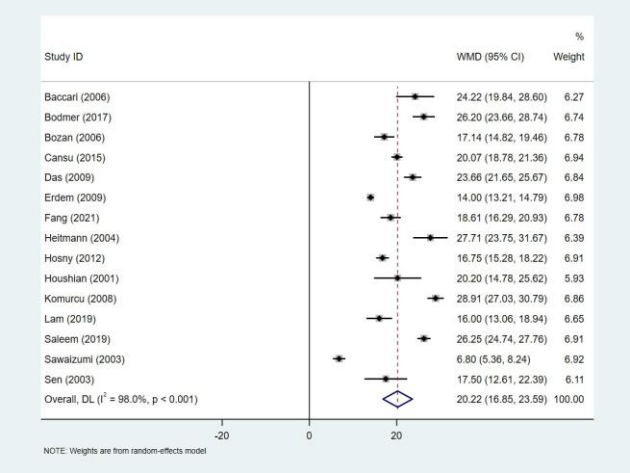


Figure S2: Forest plot of length increase (mm) in patients over 17 years of age.

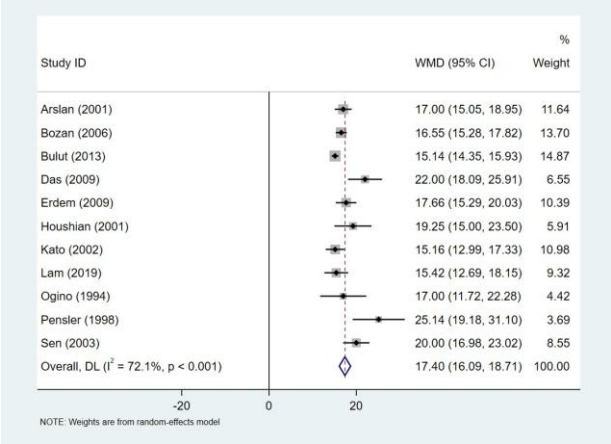


Figure S3: Forest plot of length increase (mm) in congenital metacarpal patients.

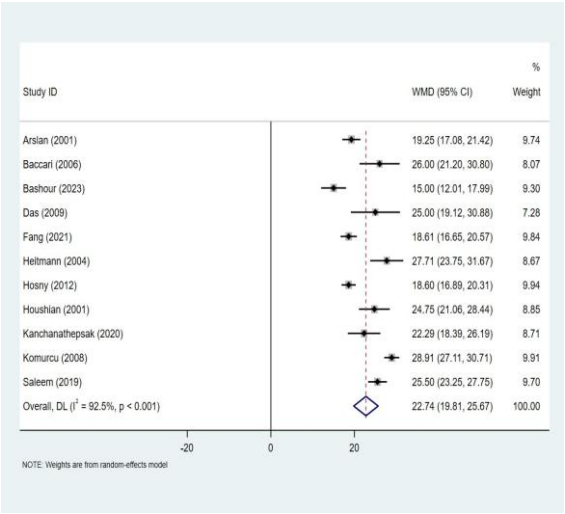


Figure S4: Forest plot of length increase (mm) in traumatic metacarpal patients.

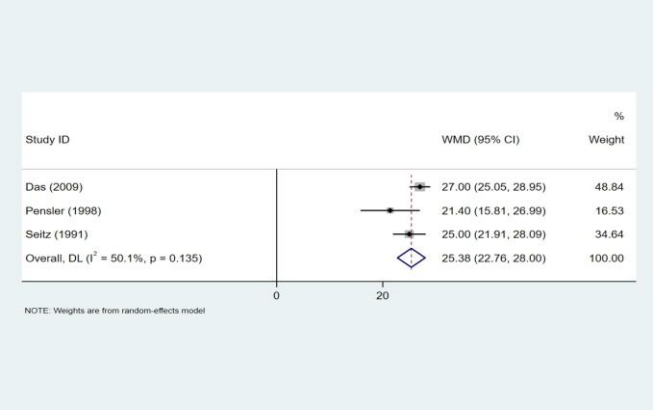


Figure S5: Forest plot of length increase (mm) in congenital phalangeal patients.

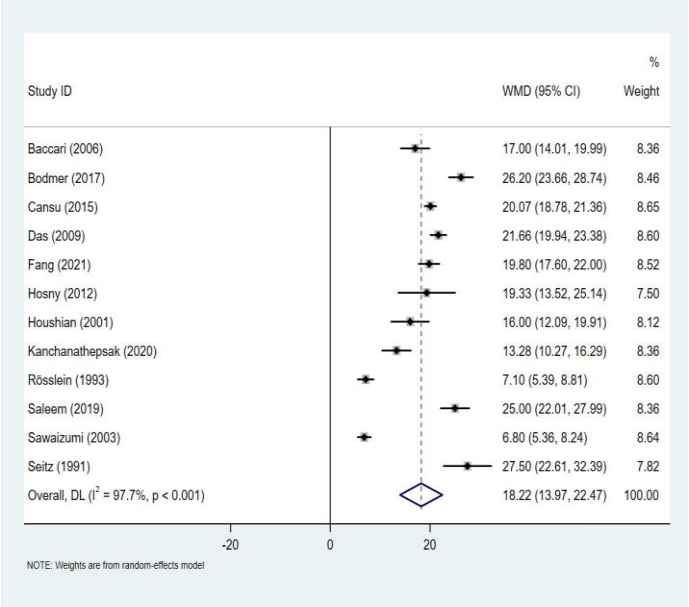


Figure S6: Forest plot of length increase (mm) in traumatic phalangeal patients.

Subgroup	Number of Studies	WMD (95% CI)	P-Value	I2 (%)
Total	38	19.81 (17.87–21.75)	p<0.001	99.1
Age				
Under 17	12	17.84 (15.24-20.44)	p<0.001	93.1
Over 17	15	20.22 (16.85-23.59)	p<0.001	98
Bone and Etiology				
Congenital Metacarpal	11	17.4 (16.09-18.71)	p<0.001	72.1
Traumatic Metacarpal	11	22.74 (19.81-25.67)	p<0.001	92.5
Congenital Phalangeal	3	25.38 (22.76-28.00)	p=0.135	50.1

Traumatic Phalangeal	12	18.22 (13.97-22.47)	p<0.001	97.7

Table 4: Subgroup Meta-Analysis Results for Length Increase (mm).

Correlational analysis

A total of 573 distraction cases were included in the correlation analysis. Complete correlation matrices are shown in Table 5. In the overall sample, grip strength correlated with distraction rate (r = -0.67), distraction time (r = 0.74), length increase (r = 0.72), and latency period (r = 1.00). Distraction rate also directly correlated with premature union (r = 0.56) (**Table 5**).

	Latency Period (day)	Distraction Rate (mm/day)	Distraction Time (day)	Consolidation Time (day)	Length Increase (mm)
Premature union incidence	-0.12	0.57	-0.24	-0.06	0.37
Non-union incidence	-0.15	0.19	-0.12	0.01	0.19
Infection incidence	0.2	-0.09	0.04	0.09	-0.02
Angulation incidence	0.08	-0.1	0	-0.03	0.02
Instability incidence	0.04	-0.15	0.48	0.02	0.11
Dislocation incidence	0.13	0.13	0.08	0.19	0.08
Grip strength (% normal side)	1	-0.67	1	-	0.72
MCP flexion (degrees)	-	0.22	-0.41	-0.34	-0.11
MCP extension (degrees)	-	-	-0.37	-0.05	-0.01

Table 5: Correlation coefficients between distraction technique parameters and complications rate Subgroup analyses

In patients under 17 years, distraction rate correlated with angulation (r = 0.64), dislocation (r = 0.65), and instability (r = 0.50). Distraction time correlated negatively with MCP extension (r = -0.65). Length increase correlated negatively with angulation (r = -0.53). Latency period correlated with angulation (r = 0.76) and dislocation (r = 0.74) (**Table S1**).

	Latency Period (day)	Distraction Rate (mm/ day)	Distraction Time (day)	Consolidation Time (day)	Length Increase (mm)
Premature union rate	-0.023	-0.02	-0.02	-0.02	-0.02
Non-union rate	-0.16	0.23	-0.01	-0.29	-0.1
Infection rate	0.32	0.04	-0.09	0.23	0.02
Angulation rate	0.77	0.64	-	-	-0.53
Instability rate	0.26	0.5	-0.12	-0.01	-0.29
Dislocation rate	0.74	0.65	-	-	-0.47
Grip strength (% normal side)	-	-	-	-	-
MCP flexion (degrees)	-	-	-0.04	-0.06	0.02
MCP extension (degrees)	-	-	-0.65	0.08	-0.28

Table S1: Correlation coefficients (r) in the under-17-year subgroup.

In patients 17 years or older, consolidation time correlated negatively with MCP flexion (r = - 0.67). Distraction rate correlated negatively with grip strength (r = -0.67) and positively with premature union (r = 0.60). Length increase correlated with grip strength (r = 0.72) and MCP extension (r = 0.58). Latency period correlated with grip strength (r = 1.00) (**Table S2**).

	Latency Period (day)	Distraction Rate (mm/ day)	Distraction Time (day)	Consolidation Time (day)	Length Increase (mm)
Premature union rate	-	**0.60**	-0.44	-	0.39
Non-union rate	-0.12	0.16	-0.18	0.10	0.27
Infection rate	0.10	-0.10	0.07	0.04	0.00
Angulation rate	-0.07	-0.17	-0.04	-0.08	0.03
Instability rate	-0.16	-0.29	0.46	-0.02	0.26
Dislocation rate	-0.03	0.08	0.01	0.12	0.11
Grip strength (% normal side)	**1.00**	**-0.67**	**1.00**	-	**0.72**
MCP flexion (degrees)	-	0.43	**-0.71**	**-0.67**	-0.43
MCP extension(degrees)	-	-	0.37	0.30	**0.58**

Table S2: Correlation coefficients (r) in the over-17-year subgroup.

In traumatic metacarpal cases, distraction rate correlated negatively with grip strength (r = - 0.67), and distraction time correlated with instability (r = 0.86). Length increase and latency period correlated with grip strength (r = 0.72 and r = 1.00, respectively) (**Table S3**). No strong correlations were observed in congenital metacarpal or traumatic phalangeal cases (**Tables S4 and S5**). In congenital phalangeal cases, infection correlated negatively with length increase (r = -0.84) and positively with latency period (r = 1.00) (**Table S6**).

	Latency Period (day)	Distraction Rate (mm/ day)	Distraction Time (day)	Consolidation Time (day)	Length Increase (mm)
Premature union rate	-	-	-0.07	-0.13	-0.16
Non-union rate	0.03	0.05	-0.22	0.33	0.03
Infection rate	-0.11	0.22	-0.19	-0.17	-0.16
Angulation rate	-0.05	-0.05	0.00	-	0.03
Instability rate	-0.13	-0.42	**0.86**	0.33	0.43
Dislocation rate	-0.03	0.15	-	0.33	0.11
Grip strength (% normal side)	**1.00**	**-0.67**	**1.00**	-	**0.72**

Table S3: Correlation coefficients (r) in traumatic metacarpal subgroup.

	Latency Period (day)	Distraction Rate (mm/ day)	Distraction Time (day)	Consolidation Time (day)	Length Increase (mm)
Premature union rate	-	-	-	-	-
Non-union rate	-	-	-	-	-
Infection rate	-0.12	-0.23	0.03	0.37	0.05
Angulation rate	0.009	-0.37	0.05	-	-0.05

Instability rate	-	-	-	-	-
Dislocation rate	-	-	0.54	0.12	0.11

Table S4: Correlation coefficients (r) in traumatic phalangeal subgroup.

	Latency Period (day)	Distraction Rate (mm/ day)	Distraction Time (day)	Consolidation Time (day)	Length Increase (mm)
Premature union rate	-0.17	0.27	-0.07	-0.08	0.25
Non-union rate	-0.19	0.04	0.23	-0.20	-0.05
Infection rate	0.19	-0.29	0.10	-0.07	-0.03
Angulation rate	-	-0.35	0.47	0.08	0.15
Instability rate	0.08	-0.27	0.27	-0.06	-0.03
Dislocation rate	-	-0.22	0.31	0.11	0.15
Grip strength (% normal side)	-	-	-	-	-
MCP flexion (degrees)	-	0.22	-0.41	-0.34	-0.11
MCP extension(degrees)	-	-	-0.37	-0.05	-0.01

Table S5: Correlation coefficients (r) in congenital metacarpal subgroup.

	Latency Period (day)	Distraction Rate (mm/ day)	Distraction Time (day)	Consolidation Time (day)	Length Increase (mm)
Premature union rate	-	-	-	-	-
Non-union rate	-0.33	-0.30	0.40	0.04	0.14
Infection rate	**1.00**	-	-0.37	-0.02	**-0.84**
Angulation rate	-	-	-	-	-
Instability rate	-	-	-	-	-
Dislocation rate	-	-	-	-	-

Table S6: Correlation coefficients (r) in congenital phalangeal subgroup.

Discussion

This meta-analysis demonstrated that distraction osteogenesis (DO) in hand surgery produces a reliable length increase, with a pooled gain of 19.81 mm across studies. This finding aligns with the fundamental DO mechanism, which harnesses controlled mechanical tension to stimulate intramembranous bone formation and new bone deposition in the fibrous inter zone during distraction [27-29]. Histologic and experimental studies have demonstrated that this process is driven by fibroblast, chondrocyte, and osteoblast activity aligned along the axis of distraction, producing longitudinally organized regenerate bone [30,31].

The wide variation in length outcomes across studies, reflected by high heterogeneity, indicates that patient-related factors (age, etiology, bone type) and technical parameters (distraction rate, latency, and consolidation time) affect the extent and quality of bone regeneration [32,33].

Age-related differences revealed that patients ≥17 years had a slightly greater average length gain (20.22 mm) than younger patients (<17 years, 17.84 mm). While prior studies [34,35] indicates that younger

patients possess higher biological regenerative capacity and faster healing due to greater cellular responsiveness, our findings suggest that adults may tolerate longer distraction durations (52 vs 26 days of distraction time; latency period of 7 days in patients aged over 17, vs 4 days in age under 17), resulting in greater final lengthening. This may reflect longer allowable consolidation periods, larger target length goals, and better mechanical stability. However, the higher heterogeneity observed in adults may also indicate greater variability in bone metabolism, comorbidities, and complication susceptibility [36, 37], as older patients typically exhibit slower bone maturation and remodeling.

Bone type and etiology significantly affected lengthening outcomes. The greatest length increase was observed in congenital phalangeal cases (25.38 mm), while congenital metacarpal cases had the lowest (17.40mm). Phalangeal bones, with smaller medullary cavities and predominantly membranous ossification, respond well to DO through rapid intramembranous bone formation. In contrast, metacarpal bones may face mechanical stress from tendons and soft tissue constraints that limit achievable distraction. Furthermore, traumatic metacarpal cases demonstrated larger gains than congenital ones (22.74 vs. 17.40 mm), likely due to preserved vascularity and intact bone architecture in post-traumatic cases, compared to congenital hypo plastic bone, which may have reduced vascularity and compromised osteogenic potential [38].

Technical parameters demonstrated strong relevance to both functional outcomes and complications. Distraction rate correlated negatively with grip strength ($r = -0.67$) and positively with premature union ($r = 0.56$), indicating that high distraction speed may compromise regenerate quality and functional recovery. Excessive distraction rate may disrupt intramembranous ossification, leading to fibrous nonunion and callus instability. Conversely, distraction time and latency period showed strong positive correlations with grip strength ($r = 0.74$ and $r = 1.00$), suggesting that longer biological adaptation periods support callus maturation and functional recovery by allowing adequate osteoblastic activity and soft tissue adaptation [17,23,38,39].

Our findings demonstrate that while extended latency period supports better functional outcomes, particularly grip strength, in adults and traumatic metacarpal cases, it is also associated with higher mechanical complications, namely angulation, dislocation, and instability, in younger and phalangeal lengthening cases. These differential responses highlight that the optimal latency duration is age- and bone-specific: younger bone and phalangeal segments may require shorter latency to prevent deformity, while older patients and metacarpal cases benefit from slightly longer latency to enhance regenerate quality and functional strength [15,23].

The extended distraction time promotes osteogenesis and functional bone strength but increases the risk of mechanical complications, especially in younger patients and traumatic metacarpal cases. This underscores the clinical need to balance distraction duration to allow sufficient bone regenerate maturation while minimizing soft-tissue overstrain and joint instability.

Consolidation time showed variable associations depending on subgroup, including negative correlation with MCP flexion in adults ($r = -0.67$) and positive correlation with MCP flexion in younger patients ($r = 0.59$). These age-related differences highlight the role of skeletal maturity in regenerate remodeling

capacity. Pediatric patients benefit from higher osteogenic potential, robust vascularity, and active bone marrow regeneration during consolidation. In contrast, adults experience slower remodeling, reduced tissue plasticity, and higher susceptibility to stiffness, making longer consolidation periods clinically relevant for predicting functional limitations rather than improved outcomes [40].

Complication profiles varied across subgroups and were strongly linked to distraction parameters. Higher distraction rates were associated with angulation, dislocation, instability, and premature union, particularly in younger patients. These complications reflect mechanically induced tissue stress and soft tissue imbalance when distraction exceeds biologic tolerance [17,39]. Infection showed strong negative correlation with length increase (r = -0.84) in congenital phalangeal cases, likely due to compromised local vascularity in congenital bone, which is less resilient to local inflammation and hardware-associated infection risk [41].

Conclusions

Taken together, our findings emphasize that DO outcomes are significantly influenced by the magnitude (distraction rate) and timing (latency, consolidation periods) of applied mechanical forces, as well as by bone quality, etiology, and age. These findings support personalized DO planning wit parameter optimization based on patient-specific factors and bone characteristics.

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