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Original paper

Metacarpophalangeal joint kinematics during a grip of everyday objects using the three-dimensional motion analysis system

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This paper deals with the way of using the device for three-dimensional motion analysis allowing the interaction between the movable segments of the hand to be described. The aims of this study were to investigate the angular patterns of the MCP joints for the fingers I–V during the grip of four commonly used objects and to compare the results between the dominant/non-dominant hands and in both male and female groups. The experiment was carried on 48 right-handed subjects (24 males and 24 females) selected at random, aged between 20 and 23. The 3-D motion capture system, that was used, consisted of 5 strobe cameras and a hand model consisting of 15 kinematic pairs with the total mobility of 20 degrees of freedom. In this study, mean, standard deviation, median, minimum, maximum and the ranges of flexion/extension and radial/ulnar deviation were separately described for each finger MCP joint. For statistical analysis and in search for the variability of angular parameters of MCP joints during a grip, the Mann–Whitney *U* test was used.

Key words: *grip patterns, MCP joint's kinematics, 3-D hand model, motion capture system*

1. Introduction

Apart from the CMCP (carpometacarpal) joint of the thumb, the MCP (metacarpophalangeal) joints of the fingers II–V are the only hand joints that have more than one degree of freedom. It is obvious that these joints have great importance for hand functionality [1], [2]. Unfortuanately, their function is very often impaired by many causes such as trauma, rheumatoid arthritis or others. The 50°-lack of flexion in MCP joints causes 24% of finger's impairement and the arthrodesis of these joints is tantamount to 55% of finger impairement [1]. In spite of the importance of the MCP joints for hand functionality, their kinematics in every day tasks is still poorly described. However, it seems to be very interesting, especially for the optimization and the improvement in hand rehabilitation programs.

So far, the systems for the analysis of the three-dimensional motion have mainly been used in the research of the human locomotion. However, it is possible to find some papers connected with the issues of the 3-D hand motion analysis and its useful application in clinical practice. CHIU et al. [3] compared the data gained during the gonimetric measurements of the finger joints' range of motion with those where the 3-D motion analysis system was used. They indicate a high convergence between these two methods. RASH et al. [4] tried to answer the question about the validity of using the 3-D video motion analysis method for the measurements of finger flexion and extension. These authors compared the analysis where motion system was used with the lateral fluoroscopy, which is regarded to be a "gold standard" of the 2-D motion measurement. They also indicated similar results, as those obtained by KUO et al. [5], who considered the thumb kinematics. Whereas DEGEORGES

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et al. [7] went a step further, by measuring the longitudinal axial rotation (LAR), which is indispensable for undisturbed finger flexion and extension. They used the 3-D optoelectronic system and compared its results with those of anatomic study previously conducted in vivo [6]. Finally, CARPINELLA et al. [8] suggested an experimental protocol of the 3-D hand kinematic analysis, which can be used in clinical practice, and verified it in the experiment with two hemiplegic patients.

The author of this paper has also carried out a research in which the 3-D motion analysis system was used for the angular description of the finger joints during a grip [9]. This paper shows that the MCP joints are the most important during a grip. The author also proposes a research method, in which the three-dimensional motion analysis system is seen as a useful device for the optimization and monitoring of hand rehabilitation process.

The aims of this study were to investigate the angular patterns of the MCP joints for the fingers I–V during the grip of four commonly used objects and to compare the results between the dominant/non-dominant hands and in both male and female groups. The parameters considered were the angular positions of each MCP joint in sagittal and frontal planes, and their percentage relation to the range of flexion (ROF) of MCP joints described by FREIVALDS [2] and DAVIDOFF and FREIVALDS [10].

2. Methods

2.1. Material

The research procedure was carried out on 48 right-handed subjects. As this research involved human beings, the author obtained the approval of the local bioethics committee. Before procedure each subject had to fill in a consent form. The age of the subjects ranged from to 20–23 years. The participants were selected at random among the student population of the University of Physical Education in Kraków. The hand lateralization was verified by filling in The Edinburgh Handedness Inventory questionnaire, which is widely accepted and reliable [11], [12]. The subjects, who disclosed in the interview any previous dysfunctions or diseases affecting hand and those who had played any sport disciplines engaging hand directly, were excluded from this investigation.

24 males and 24 females took part in the research. The basic anthropmetric data of the research group are shown in table 1.

2.2. Method

The optoelectronic three-dimensional motion capture system Vicon 250 was used for the analysis of the MCP angular joint parameters. This system consists of 5 strobe cameras, a data-station and a PC computer. 3-D position data was collected at the frequency of 120 Hz, from 26 reflective, passive markers. The diameter of each marker was 5 mm. The positions of these markers on a dorsal side of the hand are shown in figure 1 – a mirror-image shows the markers' placement on the left hand.

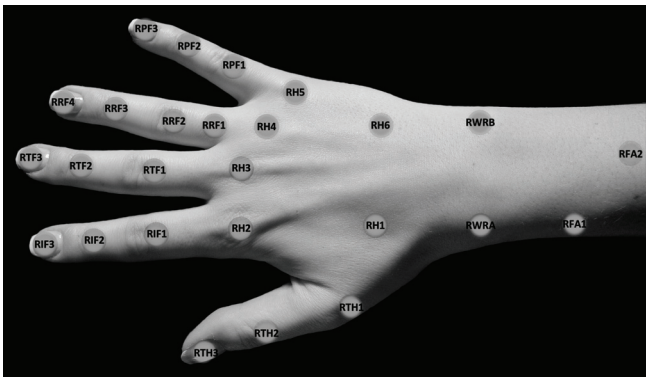

Fig. 1. The configuration of reflective markers in a RHand model

Table 1. Basic anthropometric characteristics of the research group

Anthropometric characteristics	Males				Females			
	$\bar{x}$		*SD*		$\bar{x}$		*SD*	
Height (cm)	180.0		5.9		167.6		5.8	
Weight (kg)	74.7		6.5		58.8		5.9	
	L	R	L	R	L	R	L	R
Hand length (mm)	197.6	196.9	7.7	7.7	181.9	182.6	7.1	7.3
Hand width (mm)	103.2	106.0	5.5	18.7	92.3	92.1	3.1	2.7
Metacarpus length (mm)	115.3	114.8	4.7	5.8	106.3	109.4	4.9	15.1
Metacarpus width (mm)	87.3	86.1	4.3	3.8	77.0	77.0	2.7	3.0

During the investigation the 3-D hand models RHand and LHand were used, based on the three-dimensional technique of angles calculation described by CHENG and PEARCY [13]. In these models for MCP joints, the movements are possible both in sagittal and frontal planes. The metacarpus is defined as a rigid body segment, that is why they contain 15 kinematic pairs with the total mobility of 20 degrees of freedom. The markers RH1, RH3, RH6 for the RHand model (LH1, LH3, LH6 for the LHand model) define a local reference frame and hand axes. The virtual markers RHNDV1 and LHNDV1 situated at the half of the distance between RH1 and RH6, the same as between LH1 and LH6, were the origins of the frames. The markers RH1, RH6 and LH1, LH6 are defying the *y*-axes. The *z*-axes are perpendicular to the frames created by the RH1, RH3, RH6 and LH1, LH3, LH6 planes. The *x*-axes are defined by the RHNDV1, RH3 and LHNDV1, LH3 markers. The local sagittal planes are defined by the (*z*, *x*)-axes and the frontal planes by the (*x*, *y*)-axes – see figure 2. These planes were used as the projection planes for the MCP joints' angles of the fingers II–V. The vectors representing proximal phalanges created by the RH2–RIF1, LH2–LIF1, RH3–RTF1, LH3–LTF1, RH4–RRF2, LH4–LRF2, RH5–RPF1, LH5–LPF1 markers were projected onto local sagittal and frontal planes to calculate flexion/extension and ulnar/radial deviation. For the thumb's MCP joint its flexion and its extension were calculated as the dot products of the two vectors created by the RH1–RTH1, LH1–LTH1 and RTH1–RTH2, LTH1–LTH2 markers. It should be mentioned that these two hand models described are totally independent of wrist and forearm positions and this fact was taken into consideration during the data acquisition.

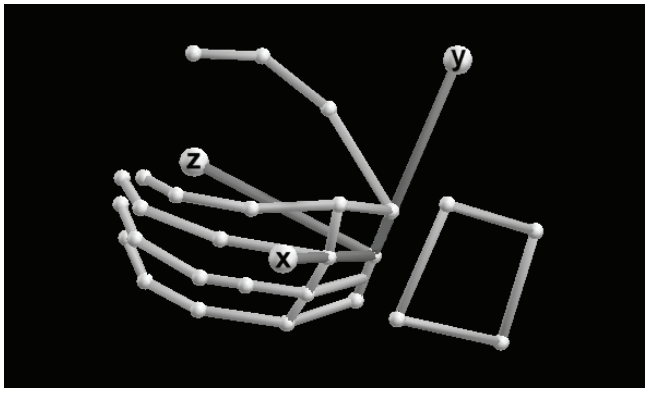

Fig. 2. The left hand model visualization during a grip of a glass – all markers and local hand axes are displayed

As is shown in figure 3, the research was carried out on 4 objects of everyday use: a glass, a ballpen, a key and a knife. In regard to the grip classifications described by FREIVALDS [2] and NORKIN [14], the grips of a ballpen, a key and a knife were considered as three-finger precision grips, involving only the thumb, the index finger and the third finger. However the grip of a glass was considered to be a power grip, in which all fingers were engaged.

Fig. 3. Evereyday objects used during the research procedure

The research procedure was conducted as follows: the data acquisition was performed on a static position of the hand joints for a couple of seconds after the considered objects had been grabbed. The subjects were required to grip objects by own way, to emphasize any possible differentiation. To optimize the 3-D data acquisition during this trial each subject was to make a small range forearm pronation and supination. It made it possible to find a frame where all the essential markers for angles calculation were projected. The research procedure was carried out firstly for the dominant hand and then for the non-dominant hand. These procedures for each object were repeated twice and the average value of these two trials was used for the statistical analysis.

2.3. Statistical analysis

The methods of descriptive and mathematic statistics were used to present the results of the study. For characterizing the angular patterns of the MCP joints of each finger (both for males and females) the following descriptive statistics were used: median – M_e, mean – $\bar{x}$, standard deviation – SD, minimum value – *Min*, maximum value – *Max*, range – *R*.

The *U* Mann–Whitney test was used to compare the gained angular values for dominant hand versus non-dominant hand and for homological hands of males and

females. The comparisons were only made for these fingers which were directly involved in the grip of each object (see chapter 2.2). Previously the distribution of variables had been checked by the Shapiro–Wilk test. Because a part of them had an abnormal distribution, the author has chosen a conservative *U* test, based on medians (M_e), for a statistical method unification. For both of the tests the *p* value was set at 0.05 level.

3. Results

Tables 2 and 3 present all descriptive statistics for angular position values in sagittal (S) and frontal (F) planes, gained during the research procedures. Because of the grips classification used, the only M_e values which underwent the comparisons in *U* test and for which all conclusions were made are marked in bold.

Considering the grip of a glass, the M_e values in sagittal plane for both hands and genders are oscillating from 23° flexion for the MCP joint of the index finger (left hand, females) to 48° flexion for the pinkie and the ring fingers (right/left hand, females). In frontal plane, all the MCP joints are presenting a few degree ulnar deviation. Whereas for all precision grips in sagittal plane, the M_e range was from 33° flexion for the index finger MCP joints (left hand, females) to 68° flexion for the thumb (left hand, males). In frontal plane, the values were ranging from 0° to 12° ulnar deviation. The smallest values of flexion angle for sagittal plane are disclosed for the grip of a glass, no matter which finger is considered. It is also a very interesting fact that the positions of joints in fronal plane always showed an ulnar deviation.

Table 4 presents the only results of the *U* Mann–Whitney test, which were statistically significant, as far as earlier mentioned comparisons are concerned (see chapter 2.3). There were a few statistically significant differences in a grip of a glass when a homological hand and gender were being concerned as the grouping variables. These differences were remarkable as well for dominant (right) hand in both planes and for non-dominant (left) hand in the sagittal plane. No other grips'

Table 2. Descriptive statistics of the MCP joint angular values (deg) during grips (males). For frontal plane (F) the minus values mean an ulnar deviation and the plus values – a radial deviation. For sagittal plane (S) plus values mean flexion. In bold are the M_e values for those fingers, which were directly engaged in a grip of an individual object

♂ (deg)		Right hand									Left hand								
		II Index		V Pinkie		IV Ring		III Third		I Thumb	II Index		V Pinkie		IV Ring		III Third		I Thumb
		MCP		MCP		MCP		MCP		MCP	MCP		MCP		MCP		MCP		MCP
		(S)	(F)	(S)	(F)	(S)	(F)	(S)	(F)	(S)	(S)	(F)	(S)	(F)	(S)	(F)	(S)	(F)	(S)
Glass	$\bar{x}$	28	–5	50	–11	49	–7	45	–6	34	27	–5	49	–10	48	–6	45	–5	36
	SD	6	10	7	9	6	6	6	7	7	6	7	8	7	7	5	7	5	6
	Min	17	–24	42	–35	36	–21	33	–20	24	18	–17	38	–22	37	–14	32	–12	25
	Max	39	11	67	5	63	2	59	6	51	41	12	66	2	63	4	59	6	50
	R	22	34	26	39	27	23	26	26	27	23	28	28	24	27	18	27	18	26
	M_e	**28**	**–6**	**48**	**–11**	**48**	**–6**	**45**	**–5**	**32**	**27**	**–6**	**48**	**–11**	**48**	**–6**	**45**	**–5**	**36**
Key	$\bar{x}$	53	–10	65	3	65	2	65	0	54	53	–10	54	–2	61	0	64	–1	54
	SD	12	7	12	8	9	5	7	7	11	10	4	16	9	10	4	7	5	8
	Min	32	–25	28	–14	46	–8	49	–12	38	31	–19	20	–19	43	–9	54	–9	40
	Max	71	3	86	18	82	12	77	18	82	68	–1	79	14	81	7	79	9	70
	R	39	28	58	32	36	20	29	29	44	37	18	59	33	38	16	25	18	30
	M_e	**55**	**–11**	**69**	**2**	**66**	**1**	**67**	**0**	**51**	**55**	**–11**	**54**	**–1**	**60**	**0**	**65**	**0**	**55**
Knife	$\bar{x}$	38	–8	69	5	67	1	56	–4	64	35	–8	59	1	57	–2	48	–4	67
	SD	10	6	11	9	9	5	6	6	10	8	6	16	12	14	5	11	5	6
	Min	23	–28	41	–21	45	–10	47	–17	48	24	–18	27	–30	30	–11	28	–15	56
	Max	53	–1	82	17	83	9	72	3	84	49	3	80	18	78	9	69	6	77
	R	31	27	42	38	38	19	25	20	36	25	21	53	48	48	20	41	20	21
	M_e	**38**	**–6**	**71**	**7**	**69**	**2**	**56**	**–4**	**62**	**35**	**–9**	**67**	**2**	**61**	**–2**	**50**	**–4**	**68**
Ballpen	$\bar{x}$	53	–7	65	3	63	1	60	–2	45	49	–8	56	1	56	–1	57	–2	50
	SD	8	7	13	9	9	5	8	6	11	10	5	12	11	11	5	9	5	9
	Min	35	–21	20	–19	47	–8	44	–14	32	25	–16	24	–27	36	–12	39	–13	37
	Max	70	3	86	20	80	10	76	8	83	66	8	75	17	77	8	79	8	71
	R	35	24	66	38	33	18	33	22	51	41	24	51	44	41	20	41	20	34
	M_e	**53**	**–8**	**64**	**3**	**63**	**1**	**58**	**–2**	**41**	**52**	**–8**	**54**	**2**	**56**	**–2**	**56**	**–2**	**51**

Table 3. Descriptive statistics of the MCP joint angular values (deg) during grips (females). For frontal plane (F) the minus values mean an ulnar deviation and the plus values – a radial deviation. For sagittal plane (S) plus values mean flexion. In bold are the M_e values for those fingers, which were directly engaged in a grip of an individual object

♀ (deg)		Right hand									Left hand								
		II Index		V Pinkie		IV Ring		III Third		I Thumb	II Index		V Pinkie		IV Ring		III Third		I Thumb
		MCP		MCP		MCP		MCP		MCP	MCP		MCP		MCP		MCP		MCP
		(S)	(F)	(S)	(F)	(S)	(F)	(S)	(F)	(S)	(S)	(F)	(S)	(F)	(S)	(F)	(S)	(F)	(S)
Glass	$\bar{x}$	23	–2	42	–18	43	–8	40	–5	30	22	–1	46	–14	46	–8	41	–5	33
	SD	7	9	13	10	9	6	8	7	7	4	8	9	8	7	6	6	7	8
	Min	10	–18	8	–46	18	–21	26	–19	17	15	–13	25	–25	31	–20	28	–20	14
	Max	33	15	59	–3	58	3	53	8	48	32	14	67	6	58	10	51	11	44
	R	23	33	51	43	40	24	27	27	31	17	27	42	31	28	30	23	31	30
	M_e	**24**	**–1**	**44**	**–17**	**45**	**–7**	**40**	**–5**	**29**	**23**	**–2**	**46**	**–14**	**47**	**–8**	**43**	**–6**	**34**
Key	$\bar{x}$	49	–11	61	0	64	1	66	–1	53	48	–10	58	–2	65	0	64	0	54
	SD	13	7	18	11	12	6	8	6	9	15	8	19	13	12	6	10	7	13
	Min	22	–26	20	–22	43	–11	50	–16	35	15	–24	13	–29	37	–12	35	–11	23
	Max	66	1	81	14	80	14	77	11	69	76	8	78	22	81	13	76	15	76
	R	44	26	62	36	37	24	27	27	34	61	32	65	51	45	25	42	25	54
	M_e	**49**	**–12**	**67**	**4**	**67**	**–1**	**69**	**0**	**54**	**49**	**–11**	**64**	**–1**	**67**	**0**	**67**	**–2**	**55**
Knife	$\bar{x}$	40	–7	68	3	60	–1	52	–4	58	35	–7	63	3	61	–2	50	–3	60
	SD	11	9	10	8	11	6	9	6	7	12	9	17	11	10	5	9	8	12
	Min	23	–31	43	–13	41	–14	33	–19	40	14	–26	10	–28	40	–13	25	–19	36
	Max	69	13	82	15	76	9	69	10	73	62	9	85	23	77	9	65	14	88
	R	47	44	40	28	36	22	37	29	33	48	35	76	51	37	22	40	33	52
	M_e	**39**	**–7**	**69**	**4**	**60**	**–2**	**50**	**–6**	**59**	**33**	**–8**	**67**	**4**	**61**	**–2**	**51**	**–5**	**60**
Ballpen	$\bar{x}$	48	–5	59	0	54	–1	56	–1	41	52	–6	57	0	60	–2	58	–1	43
	SD	10	8	15	11	14	7	11	6	11	11	9	14	10	11	6	15	7	12
	Min	19	–25	27	–23	28	–13	32	–16	23	30	–21	32	–22	42	–14	1	–16	25
	Max	66	6	79	17	76	14	74	10	62	71	18	79	19	77	12	74	14	66
	R	47	31	52	40	48	27	42	25	40	41	39	48	40	35	26	74	30	41
	M_e	**48**	**–5**	**63**	**0**	**55**	**–2**	**58**	**–1**	**43**	**50**	**–8**	**61**	**–1**	**60**	**–3**	**61**	**–2**	**42**

comparisons, respecting both dominant/non-dominant hands and genders, were statistically significant.

Table 4. The only statistically significant differences in comparisons during *U* Mann–Whitney test

Trial	Dep. variables	Grouping variables	*U* test value	*p*
Glass	MCP II (S)	Sex, R hand	2.383	0.017
Glass	MCP V (S)	Sex, R hand	2.197	0.028
Glass	MCP V (F)	Sex, R hand	2.053	0.040
Glass	MCP IV (S)	Sex, R hand	2.115	0.034
Glass	MCP III (S)	Sex, R hand	2.033	0.042
Glass	MCP III (S)	Sex, L hand	2.043	0.041
Glass	MCP II (S)	Sex, L hand	3.012	0.003
Knife	MCP I (S)	Sex, L hand	2.238	0.025
Knife	MCP III (S)	Sex, R hand	1.991	0.047
Knife	MCP III (S)	Males, R/L hand	2.538	0.011

As can be seen in figures 4 and 5 for the power grip of a glass, the percentage relation of median (M_e) angular values to the MCP joint range of flexion (ROF) approaches 50%. Only for the index fingers the values are close to 30%. For all precision grips this kind of relation is over 40% for almost all the fingers, no matter if a right or a left hand is concerned. Particularly noteworthy is the fact that for the thumb the percentage values range from about 50% (right hand, males/females, glass) to over 100% (left/right hands, males, knife). Moreover, the MCP joints of the thumb had greater percentage relation than the other ones for a ballpen, a knife and a key grips.

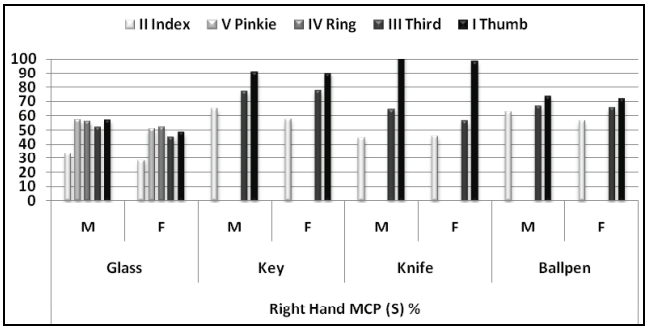

Fig. 4. The percentage relation of the right-hand MCP joint angular positions in the sagittal plane to the adequate finger MCP joint range of flexion (ROF) described by Davidoff and Freivalds (M – males, F – females)

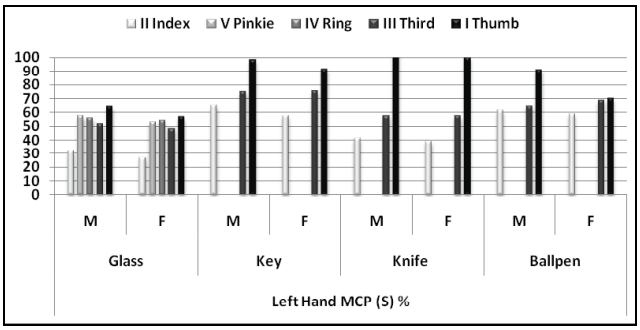

Fig. 5. The percentage relation of the left-hand MCP joint angular positions in the sagittal plane to the adequate finger MCP joint range of flexion (ROF) described by Davidoff and Freivalds (M – males, F – females)

4. Discussion

Nowadays the analysis of 3-D hand motion is more often being taken under scientific consideration. Unfortunately, it is still hard to find papers analyzing the kinematic parameters of the hand joints during daily activities for the comparison of the results with this investigation.

Hovewer, some papers corresponding to the issues of this research are available. In the trial, whose authors considered spontaneous hand movements in daily living [15], the mean values of the MCP joint angles were described. These mean values ranged from 4° for the thumb to 34° for the third finger, which made them much lower than those described in this study. BAKER et al. [16] investigated the kinematics of hand and fingers during computer keyboard use. The means of the MCP joint flexion for all the fingers of the right and left hands were 25.9° and 20°, respectively. As long as the values in frontal planes are considered, the authors of this study also revealed a small range of the ulnar deviation for all the fingers during keyboarding. In all of the previously mentioned papers, both the significantly lower number of investigation participants and a different character of finger motions probably caused that MCP joint angle values in this paper look as if they have been overestimated. On the other hand, PIENIĄŻEK et al. [17] showed that during combing, closing a zip fastener and picking up the phone the means of the MCP joint angle values for the sagittal plane ranged between 18° and 56°.

Very interesting is the fact that MCP joint angular patterns, considering the fingers directly engaged in a grip, are not as differentiated as they are supposed to be. Due to morphological differences (see table 1) it was expected to observe the statistically significant variety of the angular values, especially between genders. However the results of the comparisons in *U* test showed that actually only for dominat hand during the glass trial the differences between males and females were significant. All in all, it may be concluded that morphological differences and lateralization do not affect the angular patterns of a grip in such a way as to indicate statistically significant differences.

Based on the relation between all angular values and the ROF, it should be noticed that in almost all of the MCP joints, no matter what kind of grip is concerned, the angular positions are over 40% of the ROF. What is more, for some cases (precision grips) a 100% of the MCP range of flexion was needed. This confirms that a full mobility of the MCP joints is essential to make an effective grip possible.

To sum up, the research procedure presented in this paper has limitations, especially because of the simplified 3-D hand model, which only allows measurements of the dynamic angular changes or static angular position of finger joints. No other kinematic parameters could be estimated. However, in the literature it is possible to find some papers where 3-D hand models and research protocols are used, which make it possible to conduct a more detailed kinametic analysis of the finger joints [16], [18].

The issues of the finger motion analysis should be interesting especially for hand therapists and surgeons due to the treatment and rehabilitation process. That kind of study based on the 3-D hand motion analysis, where motion capture systems or sensor/data gloves [19], [20] are used, should help them to improve and to optimize the hand treatment programs, which make the full recovery of an impaired hand possible with gaining the best functional outcome.

5. Conclusions

Based on all gained results, it is possible to conclude that for both precision and power grips, the mobility of over 40% of the MCP range of flexion in the sagittal plane and the ulnar deviation are essential to enable an effective grip of objects, as used in this investigation. Beside the grip of a glass for the dominant hand, neither gender nor lateralization affect the MCP joint angular patterns of a grip on a statistically significant level. The results of this paper should be taken under consideration by any hand surgeon and therapist to provide the very best hand functional outcome.

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