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Functional range of motion in the upper extremity and trunk joints: Nine functional everyday tasks with inertial sensors

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ABSTRACT

Background: Functional range of motion is defined as the required range of motions for individuals to maintain maximal independence, along with optimal conditions for activities of daily living. Intervention plans for rehabilitation are directed towards the acquisition of anatomical range of motion. However, this isn't always possible based on person's etiology, prognosis, or severity of disease.

Research question: The aim of this study is to determine functional range of motion during different unilateral, bilateral symmetrical and bimanual asymmetrical tasks of activities of daily living.

Methods: Participants completed nine basic activities of daily living (hand to head, hanging jacket, eating, wallet placement to back pocket, washing hands and face, removing belt, water pouring, brushing teeth) linked according to International Classification of Functioning, Disability and Health, while joint kinematics of the trunk and upper extremity were recorded with inertial measurement units. Peak values of mean joint angles were determined for each activities of daily living. MVN BIOMECH Awinda MTW2-3A7G6 sensors (Xsens Technologies B.V. Enschede, Netherlands) were used for 3D kinematic analysis of activities.

Results: Forty-six healthy subjects (right-dominant) were included in this study. Range of motion requirements of all activities were defined 37.85° extension, 91.18° flexion, 1.25° adduction, 39.45° abduction, 63.6° internal rotation, 21.8° external rotation in the dominant shoulder, 124.17° flexion in the dominant elbow, 40.29° extension, 23.66° flexion, 18.31° supination, 12.56° pronation, 18.27 ulnar deviation and, 18.36° radial deviation in the dominant wrist. Maximum trunk range of motions were found to be 29.75° flexion in C7-T1, 10.74° flexion in T12-L1, and 24.16° flexion in L5-S1.

Significance: It is thought that the results of this research will contribute to the determination of normative data needed for surgical interventions, technological rehabilitation devices and task-spesific rehabilitation programs which based patient's motor skill level.

1. Introduction

The normal kinematic features of basic activities of daily living (ADLs) such as eating, drinking, personal care, functional mobility, wearing depend on range of motion (RoM), speed, efficacy, accuracy, smoothness and coordination between the joints of the trunk and upper extremity [1]. Especially, RoM in all directions are essential for ADLs. When ADLs were impeded due to decreased RoM, these ADLs were performed by using compensatory movement or assistance of other peoples and adaptive instruments [2]. Therefore, maintaining or restoring RoM is the main objectives of many rehabilitation practices [2].

Intervention plans for rehabilitation usually directed towards the acquisition of anatomical maximal RoM of joints [2]. But, it is not always possible in relation to etiology, prognosis, or severity of the disease such as burn injury, muscle shortness, tendon or ligament contractures, pain, muscle tone disorders, adhesive capsulitis, bone fractures, plexus lesions, rheumatoid arthritis, and others [2–9]. All of these informations reveal the need to determine the functional RoMs defined as required maximal range of motion without limitations while performing different daily tasks [10].

Kinematic analysis is an objective method for evaluating of functional RoM to describe the extremities and trunk movements during

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ADLs [10,11]. In previous studies, electromagnetic systems [5,12,13] and optical systems [14–18] were used for determining functional RoMs of upper extremity joints. These systems can be provide valid, reliable, detailed and objective measurements [19] but spesific materials of these systems have difficult accessibility because of materials are relatively expensive, non-portable and require a well-trained biomechanical expertise. Therefore, the usability of these systems is not common in clinical practice, and clinicans do not have access to objective data for evaluating patient's impairment or motor performance. A more accessible methods needed to evaluate RoM in clinics [20]. In this respect, inertial measurement units (IMUs) are used to evaluate the performance of the upper limb motor function during ADLs in the literature [20–23]. Furthermore, potential solutions of IMUs allows to determine kinematics without being restricted to laboratory area and clinicians who inexperienced in the field of biomechanics can evaluate individuals easily in clinical settings [20]. IMUs are portable and more cheaper than camera based motion-capture systems. Also, the validity of joint kinematic assesments of IMUs has been confirmed with respect to optoelectronic motion analysis systems [20,24–26].

In previous studies, shoulder and elbow joint RoMs were analyzed for 66 different ADL tasks which 40 focused personal care, seven on feeding, and the rest on variety of daily, leisure, and work activities [2]. According to our knowledge, functional RoMs of the upper extremity and spesific trunk joints were not evaluated together. Additionally, there is no study investigating the kinematic properties of bimanual asymmetric activities (e.g. water pouring, removing belt, teeth brushing) which right and left upper extremities have different tasks at the same time. In this context, the purpose of present study is to define the functional RoM of the upper limbs and trunk joints in healthy individuals during unilateral (hand to head, hanging jacket, eating and wallet placement to back pocket) and bilateral-bimanual (washing face and hands, remove belt, brushing teeth, water pouring) functional everyday tasks.

2. Material and methods

2.1. Participants

The individuals who are 20–40 years old, right dominant, have painless upper extremity and trunk movement were included in this study. The individuals who have diagnosed the neurological or orthopedic problem that prevents upper extremity and trunk movements were excluded. This study was conducted in the Hacettepe University, Faculty of Health Sciences, Department of Physiotherapy and Rehabilitation, Technological Rehabilitation Research Laboratory. Written informed consent was obtained from all participants, as approved by the Ethics Committee of the Hacettepe University (KA-17051). Physical and demographic characteristics (age, weight, height, body mass index, flare length, distance between right and left acromion) of the participants were all recorded.

2.2. Experimental protocol

MVN BIOMECH Awinda MTW2-3A7G6 sensors (Xsens Technologies B.V. Enschede, Netherlands) were used for 3D kinematic analysis of activities. IMUs consist of a triaxial accelerometer, triaxial magnetometer and triaxial gyroscope. A kalman filter (Xsens Kalman Filter, XKF) was used to generate 3D reconstruction for body segment position and orientation. These sensors tend to yield valid and reliable results compared to optical motion analysis systems, which had been accepted as the gold standard in prior studies of biomechanical analysis [20,24–27].

Bilateral shoulder, elbow, wrist, and C7-T1, T12-L1, L5-S1 joint kinematic data were recorded with IMU sensors, wireless station and Xsens MVN Studio 4.6 was used to follow the IMU orientations with respect to an earth-based coordinate frame [28]. The biomechanical model of this system associated with a model from Optotrak motion-based system [29,30]. Thus, this system able to quantify joint kinematics of complex movements [20]. Gloves, vests, and velcro tapes were used to affix sensors to upper extremity and trunk for an effective analysis.

The participant was asked to stand N-Pose for calibration process, as intructions in MVN BIOMECH user manual. Measurements were evaluated for individuals in an anatomical position, performing activity, and then returning to the anatomical position. Each measurement was repeated three times with 60 s intervals. The mean values of kinematic data determined each individual's functional RoM of joints. The joint angle definitions followed by the International Society of Biomechanics [31]. Characteristics of materials, as well as their measurements, were standardized for every individual.

2.3. Activities

Nine ADLs were selected by examining the studies in the literature [12,13,32,33] and associated clinical experience of study group with International Classification of Functioning, Disability and Health (ICF) subdomains. ICF linking process was constructed by three PhD physiotherapist and they followed Cieza et al.'s linking rules [34]. Within the scope of the study ***unilateral;*** hand to head (HTH), hanging jacket (HJ), eating (EAT), wallet placement to back pocket (WPBP), ***bilateral symmetric;*** washing hands and face (WH−WF), and ***bimanual asymmetric;*** removing belt (RB), water pouring (WPo), brushing teeth (BT) activities were evaluated. Activity selection criteria showed in Table 1.

2.3.1. Unilateral activities

- **Hand to head:** Participants were asked to touch their right hand to the center point of their head.
- **Hanging jacket:** Participants were asked to hang a standard jacket to 175 cm height hanger and they were positioned 30 cm opposite the center of hanger.
- **Eating:** Participants were asked to sit in an upright position on 45 cm height chair. The plate and spoon were placed 15 cm forward on 75 cm height table. The participants were asked to take the spoon 3 times to their mouths with their right hands.
- **Wallet placement to back pocket:** The wallet was placed 15 cm forward on 75 cm high table. The participants were asked to take wallet and put their back pocket.

2.3.2. Bilateral symmetric activities

- **Washing face and hands:** A basin was laid on 75 cm high table for representing the washbowl. The participants were asked to do these activities in a similar way as they did in daily life. However, water was not used performing the activities. Each participant washed his hands three times. The WF activity was performed in same protocol.

2.3.3. Bimanual asymmetric activities

- **Removing belt:** Each participant was asked to wear the appropriate belt and stand anatomical position. The participants were asked to remove belt using both hands and keep it in the right hand.
- **Brushing teeth:** The toothpaste and toothbrush were placed on the shelf of 125 cm height. The distance between toothpaste and toothbrush was 15 cm and they placed parallel to each other. Firstly, the participants were asked to take toothbrush with right hand and take toothpaste with left hand on the shelf. Secondly, the participants were asked to squeeze toothpaste into toothbrush and put

Table 1
Activity selection protocols and ICF linking.

Activity	Type	Related ADL	Linked ICF Parameters	Referred Article
Hand to head	Unilateral / Head over	Personal Care	d5202, Caring for hair.	Similiar, Aizawa et al. [12], Magermans et al. [5], van Andel et al. [8]
Hanging jacket	Unilateral / Head over	Functional Mobility	d540, Dressing.	None
Eating	Unilateral / Sitting	Eating	d550, Eating.	Magermans et al. [5]
Wallet placement to back pocket	Unilateral/ Outside Visibility Area	Toilet Hygiene, Functional Mobility	d5301, Regulation defecation.	Similiar, van Andel et al. [8]
Washing hands	Bilateral/ Symmetrical	Personal Care	d5100, Washing body parts.	Bible et al. [44,45]
Washing face	Bilateral/ Symmetrical	Personal Care	d5100, Washing body parts.	None
Removing belt	Bimanuel asymmetrical	Wearing	d5401, Taking off clothes.	None
Brushing teeth	Bimanuel Asymmetrical /Multi Motor Tasks	Personal Care and Hygiene	d5201, Caring for teeth.	Inada et al. [33]
Water Pouring	Bimanuel Asymmetrical /Multi Motor Tasks	Eating and Functional Mobility	d560, Drinking.	Aizawa et al [12].

toothpaste on the shelf. Thirdly, the participants were asked to brush three times circularly with toothbrush on their right hand and put toothbrush on the shelf.

- **Water pouring:** The pitcher and glass were placed on the 45 cm high table. The distance between pitcher and glass was 15 cm. Pitcher filled with 1 L of water. Firstly, the participants were asked to lean forward to take pitcher (with right hand) and glass (with left hand) to upward simultaneously. Secondly, the participants were asked to fill the glass with water from pitcher. Lastly, the participants were asked to put glass and pitcher to table.

2.4. Statistical analysis

Statistical analysis was performed with the MATLAB R2016a (MathWorks, Natick, MA, USA). The weighted linear regression method was used for normalization, while descriptive statistics were given with mean ± standard deviation (X ± SD).

3. Results

Forty-six (22 males, 24 females) healthy subjects were included. The mean age was found to be 25,74 ± 4,18 years. The mean height and flare length was found to be 171,22 ± 8,22 and 170,60 ± 10,16 cm. The mean length between bilateral acromions was found to be 32,91 ± 3,84 cm. The mean weight was found to be 67,33 ± 15,11 kg and the mean body mass index was found to be 22,73 ± 3,55 kg / m^2.

The maximum angles and functional RoMs of the unilateral tasks, bimanual asymmetrical activities, bilateral symmetrical tasks, are shown in Tables 2–4. The functional extension/flexion range of joints showed in Fig. 1.

With this study, lateral flexion of T12-L1 joint and rotation of C7-T1, L5-S1 and shoulder joints showed highest RoM degrees in HJ; the lateral flexion of C7-T1 and L5-S1 joints were highest in WPBP. The ulnar/radial deviation range of the wrist was highest in WPo. The abduction/adduction range of the dominant shoulder, pronation/supination range of the dominant wrist, and flexion/extension range of dominant elbow were highest in BT (Table 3).

The pronation/supination range of the dominant elbow was highest in WH and flexion/extension range of C7-T1 joint was highest RB, flexion/extension range of T12-L1, L5-S1, and dominant wrist joints were highest in WF. Also, functional RoMs of dominant and non-dominant extremities were found similiar in bilateral symmetrical tasks (Table 4).

4. Discussion

Studies evaluating the upper extremity kinematic characteristics of daily living activities in healthy individuals play an important role in establishing the reference values needed for accurate and objective determination of activity limitations in various diseases [2,8]. Therefore, studies are needed to evaluate upper extremity activities under different conditions in the literature. Also trunk stabilization plays fundamental role for the quality and accuracy of upper extremity movements [35,36]. Most of the previous studies, ignoring this situation, the only upper extremity kinematics investigated [2,17,33,37]. In this respect, this study differs from literature in terms of investigate the trunk and upper extremity movements with IMU sensors.

The activities included in previous studies were chosen according to different approaches. The activities were selected from the parameters of the functional evaluation scales [12,13,18], patients' feedbacks [38,39], and pilot or previous studies in the literature [11,40,41]. In this study, activities were selected from the previous studies, and clinical experience of the research team, and activities are associated with the sub-domains of ICF. For this reason, this is the first study in which ICF linking is used systematically in kinematic research.

In the previous studies, the activities were evaluated in the

Table 2
Functional range of motions of dominant extremity and trunk during unilateral tasks.

Joints	Activities	Right (+) / Left (-) Lateral Flexion					Right (+) / Left (-) Axial Rotation					Flexion (+) / Extension (-)				
		Minimum		Maximum		Range	Minimum		Maximum		Range	Minimum		Maximum		Range
		Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
C7-T1	**HTH**	0,22	1,27	3,13	1,81	2,91	−0,47	1,74	1,06	1,97	1,53	19,3	2,86	20,68	3,13	1,38
	HJ	−0,94	1,32	2,35	1,8	3,29	−5,4	3,7	1,57	2,56	6,97	9,96	3,66	14,68	3,87	4,72
	EAT	−0,2	1,36	2,46	2,13	2,66	−0,55	1,78	0,05	2,7	0,6	15,52	3	18,31	3,53	2,79
	WPBP	−0,49	0,97	3,6	2,62	4,09	−3,89	2,29	0,56	2,45	4,45	18,25	3,91	23,49	5,52	5,24
T12-L1	**HTH**	−0,55	0,39	0,06	0,29	0,61	−0,34	0,73	−0,06	0,74	0,28	0,88	0,66	1,08	0,63	0,2
	HJ	−1,42	1,05	0,39	0,57	1,81	0,66	1	2,59	1,27	1,93	0,54	1,21	1,07	1,13	0,53
	EAT	−0,17	0,83	0,46	0,7	0,63	−0,05	0,92	0,31	1,06	0,36	5,05	2,06	8,63	1,9	3,58
	WPBP	−0,5	0,79	0,8	0,91	1,3	−0,76	1,17	1,96	1,02	2,72	1,01	0,76	3,36	1,18	2,35
L5-S1	**HTH**	−1,23	0,88	0,13	0,64	1,37	−0,77	1,65	−0,14	1,66	0,63	1,97	1,49	2,43	1,41	0,46
	HJ	−3,22	2,33	0,85	1,31	4,08	1,48	2,25	5,81	2,87	4,33	1,13	2,76	2,41	2,54	1,28
	EAT	−0,44	1,85	1,01	1,55	1,45	−0,05	2,07	0,66	2,41	0,71	11,38	4,64	19,43	4,3	8,05
	WPBP	−1,06	1,74	1,65	2,02	2,71	−1,75	2,63	4,47	2,3	6,22	2,27	1,71	7,58	2,65	5,31
Shoulder		**Abduction (+) / Adduction (-)**					**Internal (+) / External (-) Rotation**					**Flexion (+) / Extension (-)**				
Right	**HTH**	9,57	4,33	38,89	10,89	29,32	−13,09	8,63	55,4	18,5	68,49	4,85	5,47	89,88	21,33	85,03
	HJ	8,17	5,26	30,21	12,77	22,04	−13,71	11,89	63,62	16,51	77,33	−6,9	7,92	91,18	14,24	98,08
	EAT	10,27	5,05	31,84	10,16	21,57	−9,82	10,11	21,4	12,78	31,22	4,41	7,04	46,03	14,99	41,62
	WPBP	9,28	3,87	22,7	8,33	13,42	−21,77	12,41	20,97	14,18	42,74	−37,85	10,68	21,52	15,25	59,37
Wrist and Elbow		**Ulnar (+) / Radial (-) Deviation**					**Pronation (+) / Supination (-)**					**Flexion (+) / Extension (-)**				
Right Wrist	**HTH**	2,81	5,63	5,55	7,43	2,74	−18,31	11,75	−11,45	10,16	6,86	−9,05	9,09	7,8	11,23	16,85
	HJ	−9,74	9,12	8,86	10,69	18,6	−13,72	13,43	7,1	10,68	20,82	−28,96	15,53	−9,05	15,99	19,91
	EAT	−1,98	10,4	5,9	11,58	7,88	−15,45	13,68	−1,41	11,2	14,04	−40,29	12,61	−12,46	10,63	27,83
	WPBP	−1,87	8,88	4,85	8,86	6,71	−18,19	12,78	3,27	17,57	21,46	−30	14,29	−4,36	23,66	25,64
Right Elbow	**HTH**	*	*	*	*	*	22,6	16,03	55,09	18,44	32,49	8,56	7,66	110,9	22,48	102,34
	HJ	*	*	*	*	*	14,58	17,2	83,87	24,78	69,29	10,13	8,63	91,67	20,81	81,54
	EAT	*	*	*	*	*	18,68	16,91	67,23	22,71	48,55	13,84	9,07	120,6	16,81	106,76
	WPBP	*	*	*	*	*	14,8	18,35	107,93	23,89	93,13	11,43	7,48	50,83	35,9	39,4

HTH: Hand to head, HJ: Hanging jacket, EAT: Eating, WPBP: Wallet placement to back pocket, *: Not analyzed.

Table 3
Functional range of motions of dominant extremity and trunk during bimanual asymmetrical tasks.

Joints	Activities	Right (+) / Left (-) Lateral Flexion					Right (+) / Left (-) Axial Rotation					Flexion (+) / Extension (-)				
		Minimum		Maximum		Range	Minimum		Maximum		Range	Minimum		Maximum		Range
		Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
C7-T1	**RB**	0,01	1,19	2,03	2,16	2,02	−0,19	1,84	0,31	2,08	0,5	17,52	3,44	29,75	5,58	12,23
	WPo	−0,98	2,32	0,67	1,97	1,65	−0,36	1,31	1,51	1,29	1,87	18,95	4,07	23,68	3,51	4,73
	BT	−1,01	1,1	0,84	1,67	1,85	1,26	2,23	2,12	2,43	0,86	17,12	3,13	20,62	3,58	3,5
T12-L1	**RB**	0,17	0,5	0,35	0,44	0,18	0,35	0,58	0,79	0,99	0,44	1,4	1,56	3,23	2,29	1,83
	WPo	−1,34	0,81	−0,01	0,66	1,33	−0,04	0,34	0,4	0,62	0,44	1,21	0,75	6,26	2,43	5,05
	BT	−0,57	0,42	0,05	0,29	0,62	0,34	0,87	0,69	0,84	0,35	0,8	0,71	1,55	0,95	0,75
L5-S1	**RB**	0,35	1,15	0,78	0,96	0,43	0,79	1,3	1,77	2,22	0,98	3,16	3,51	7,27	5,15	4,11
	WPo	−3,04	1,83	−0,01	1,44	3,03	−0,1	0,76	0,85	1,4	0,95	2,72	1,69	14,09	5,47	11,37
	BT	−1,3	0,97	0,11	0,66	1,41	0,74	1,96	1,53	1,89	0,79	1,79	1,59	3,48	2,14	1,69
Shoulders		**Abduction (+) / Adduction (-)**					**Internal (+) / External (-) Rotation**					**Flexion (+) / Extension (-)**				
Right	**RB**	9,23	5,01	19,4	5,91	10,17	−12,76	12,45	9,68	12,76	22,44	−11,86	10,61	2,13	10,56	13,99
	WPo	8,55	3,94	27,16	10,36	18,61	−12,32	8,22	20,99	10,58	33,31	1,52	4,84	35,92	9,85	34,4
	BT	8,19	4,08	39,45	10,68	31,26	−10,47	9,16	24,98	13,76	35,45	−1,18	6,78	55,01	14,4	56,19
Left	**RB**	10,08	4,49	19,64	5,57	9,56	−8,96	10,7	12,02	13,01	20,98	−6,76	9,61	5,83	8,39	12,59
	WPo	822	4,9	11,82	6,36	3,6	−9,11	9	23,38	10,8	32,49	2,84	4,25	32,36	12,79	29,52
	BT	9,18	4,08	23,98	11,5	14,8	−15,82	10,26	21,67	13,55	37,49	−1,41	5,05	42,49	13,92	43,9
Wrists		**Ulnar (+) / Radial (-) Deviation**					**Pronation (+) / Supination (-)**					**Flexion (+) / Extension (-)**				
Right	**RB**	−8,69	9,04	5,69	9,28	14,38	−13,95	13,72	3,78	12,83	17,73	−19,18	13,2	−3,94	13,24	15,24
	WPo	−11,68	9,38	16,96	8,96	28,64	−17,76	11,43	9,5	12,37	27,26	−24,94	11,22	−9,59	8,97	15,35
	BT	−18,27	9,71	2,59	8,53	20,86	−14,78	11,45	12,56	11,92	27,34	−18,09	13,39	−5,9	11,48	12,19
Left	**RB**	−9,51	10,56	3,1	5,88	12,61	−16,41	13,28	3,47	12,37	19,88	−13,08	14,32	1,92	13,36	15
	WPo	3,12	4,51	20,93	11,71	17,81	−17,63	11,26	1,71	6,58	19,34	−27,06	10,11	−7,21	7,97	19,85
	BT	−21,43	12,17	2,9	8,59	24,33	−17,65	11,25	12,63	10,24	30,28	−14,62	12,33	−5,3	14,34	9,32
Elbows		**Ulnar (+) / Radial (-) Deviation**					**Pronation (+) / Supination (-)**					**Flexion (+) / Extension (-)**				
Right	**RB**	*	*	*	*	*	16,64	17,12	81,09	24,97	64,45	10,26	8,8	63,96	18,78	53,7
	WPo	*	*	*	*	*	24,73	15,68	114,15	16,18	89,42	11,5	7,16	76,05	15,58	64,55
	BT	*	*	*	*	*	18,5	15,58	108,47	24,36	89,97	10,45	8,43	124,17	11,28	113,72
Left	**RB**	*	*	*	*	*	20,51	18,57	92,77	24,95	72,26	9,27	7,35	61,02	22,27	51,75
	WPo	*	*	*	*	*	22,81	15,52	114,05	14,64	91,24	10,61	7,28	56,83	16,04	46,22
	BT	*	*	*	*	*	26,82	17,73	112,63	23,73	85,81	8,52	6,83	87,69	14,59	79,17

RB: Removing Belt, WPo: Water Pouring, BT: Brushing Teeth, *: Not analyzed.

Table 4
Functional range of motions of dominant extremity and trunk during bilateral symmetrical tasks.

Joints	Activities	Right (+) / Left (-) Lateral Flexion					Right (+) / Left (-) Axial Rotation					Flexion (+) / Extension (-)				
		Minimum		Maximum		Range	Minimum		Maximum		Range	Minimum		Maximum		Range
		Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
C7-T1	**WH**	0,02	1,21	1,2	2,38	1,18	−0,24	1,63	0,32	1,39	0,56	17,26	3,34	21,54	3,9	4,28
	WF	−0,13	1,28	1,77	2,03	1,9	−0,77	1,88	0,08	2,2	0,85	11,37	4,36	20,5	3,54	9,13
T12-L1	**WH**	0,02	0,36	0,13	0,63	0,11	0,07	0,39	0,76	0,73	0,69	0,59	0,95	7,6	1,93	7,01
	WF	0,09	0,34	0,29	0,79	0,2	0,04	0,4	1,04	0,94	1	0,86	1,11	10,74	1,65	9,88
L5-S1	**WH**	−0,02	0,86	0,21	1,35	0,23	0,16	0,88	1,7	1,68	1,54	1,32	2,14	17,1	4,35	15,78
	WF	0,09	0,86	0,57	1,63	0,48	0,09	0,9	2,34	2,06	2,25	1,93	2,5	24,16	3,72	22,23
Shoulders		**Abduction (+) / Adduction (-)**					**Internal (+) / External (-) Rotation**					**Flexion (+) / Extension (-)**				
Right	**WH**	8,37	4,26	13,95	7,32	5,58	−12,06	8,02	31,08	10,87	43,14	−3,94	5,39	44,37	11,53	48,31
	WF	−1,25	7,22	14,03	9,9	15,28	−11,92	8,13	37,19	11,39	49,11	−3,51	5,69	57,49	14,76	61
Left	**WH**	6,93	6,23	13,02	6,8	6,09	−12,49	8,94	30,75	10,44	43,24	−0,56	4,58	44,85	11,29	45,41
	WF	−2,52	7,92	13,92	10,16	16,44	−10,93	8,63	37,5	12,02	48,43	−0,07	4,93	56,43	13,04	56,5
Wrists		**Ulnar (+) / Radial (-) Deviation**					**Pronation (+) / Supination (-)**					**Flexion (+) / Extension (-)**				
Right	**WH**	2,19	6,02	8,58	12,69	6,39	−16,77	10,96	−0,72	12,93	16,05	−18,49	14,68	−7,89	22,56	10,6
	WF	3,19	5,82	18,36	10,63	15,17	−17,06	11,81	−6,49	11,36	10,57	−39,6	13,07	−10,14	10,3	29,46
Left	**WH**	0,53	8,15	8,48	15,92	7,95	−18,89	11,85	−5,2	9,89	13,69	−17,09	14,76	−3,55	19,4	13,54
	WF	3,69	4,99	17,28	12,83	13,59	−18,76	11,18	−10,81	9,16	7,95	−37,8	15,79	−7,31	8,62	30,49
Elbows		**Ulnar (+) / Radial (-) Deviation**					**Pronation (+) / Supination (-)**					**Flexion (+) / Extension (-)**				
Right	**WH**	*	*	*	*	*	23,6	18,54	101,89	35,94	78,29	10,98	8,6	64,07	15,12	53,09
	WF	*	*	*	*	*	25,6	18,68	93,52	22,82	67,92	12,19	9,01	119,8	15,7	107,61
Left	**WH**	*	*	*	*	*	22,44	17,68	95,92	41,11	73,48	9,43	7,72	61,88	15,84	52,45
	WF	*	*	*	*	*	23,73	17,63	90,23	25,56	66,5	9,78	8,04	119,73	16,17	109,95

WF: Washing Face, WH: Washing Hands. *: Not analyzed.

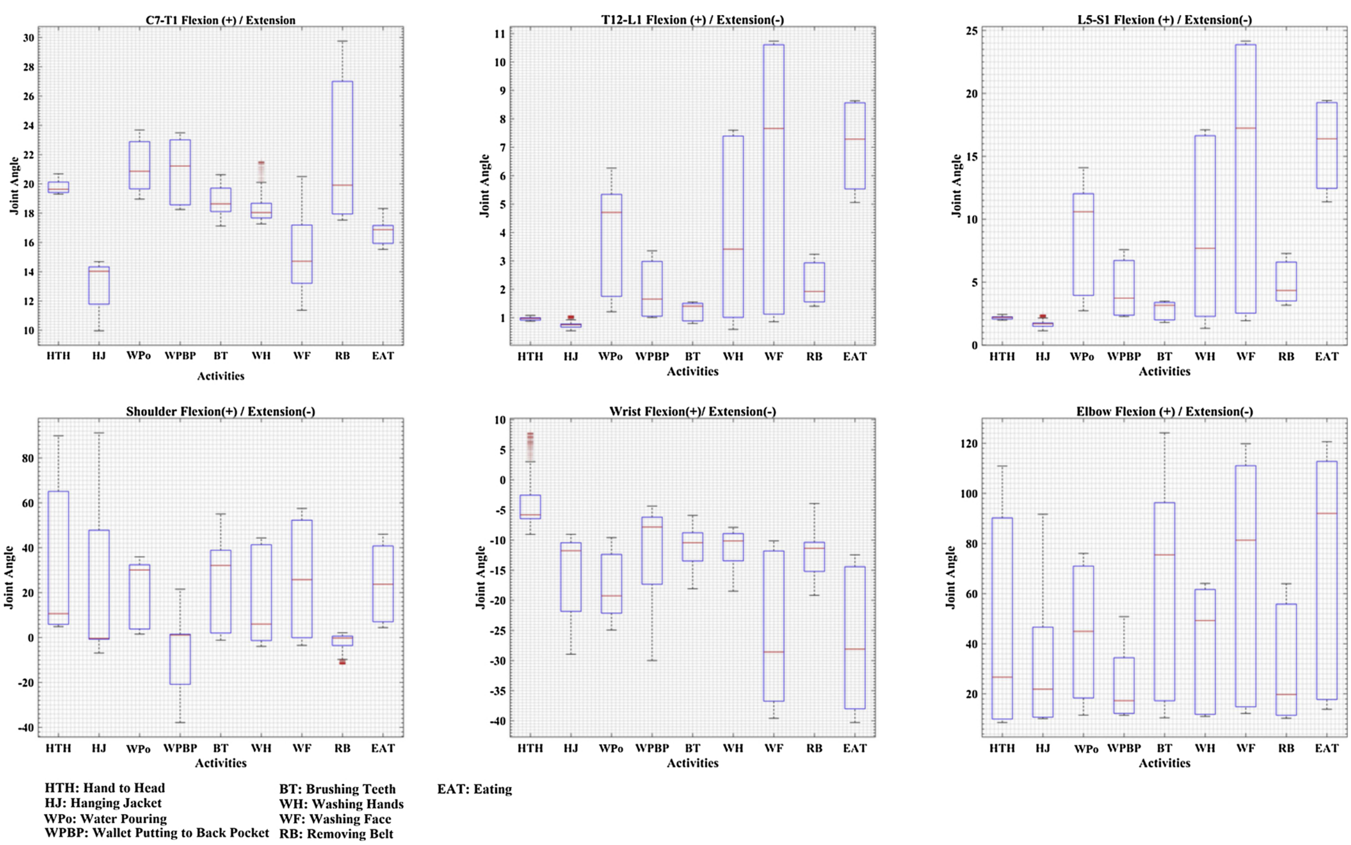

Fig. 1. Joint's functional range of motion on flexion/extension movement.

unilateral pattern including the daily life requirements of personal care, nutrition, functional mobility and communication [2,10]. However, from functional point of view; most of the activities in our daily life involve the simultaneous use of both hands in sametime. For example; shopping, dressing, cooking, driving, keyboard writing activities are largely based on the use of two upper extremities [42]. It is known that bilateral extremities perform different functions simultaneously in a complementary manner. Besides the unilateral upper extremity kinematics, there is a need for the assessment of symmetrical and asymmetrical bimanual activities for determine the targets for rehabilitation correctly. In this respect, this study is the first to evaluate the trunk and upper extremity joints concurrently with IMU sensors during bilateral symmetrical (WH, WF) and bimanual asymmetrical activities (WPo, RB, CT).

In a comprehensive review of the literature, the functional RoMs in the shoulder joint were approximately 62° extension, 142° extension/flexion, 115° abduction, and 127° adduction [2]. In previous studies, functional RoMs were found 121°-135.7° flexion, 53° supination and 13°-120° pronation in the elbow joint and 50° extension, 45° flexion, 23-40° ulnar deviation, and 15°-28° radial deviation in the wrist joint [5,32,43]. A few studies assessed functional RoMs of cervical and lumbar joints during ADLs [44,45]. According to Bible et al. cervical functional RoMs during the 15 ADLs were 13° extension 32° flexion, 9°-21° lateral bending, and 13°-57° axial rotation [44] and lumbar functional RoMs were 3° extension, 49° flexion, 2°-11°lateral bending, and 2°-7° axial rotation [45]. In these studies, multi-joint RoMs were described. Each joint was not examined separately, and it is not known which joint belongs to the ROM. In this respect, this study measured the trunk from different levels for the first time and gave more detailed results compared to the literature. Furthermore, functional RoMs of upper extremity and trunk joints were found smaller than previous studies. It is thought that the differences between this study and the literature are due to measurement methods and protocols and the results of our study will contribute to increase the activity diversity on the literature.

During the bimanual asymmetric activities (WPo, RB, BT) evaluated within the scope of the research, the mean values of the functional RoMs were 23.98° adduction, 15.82° external rotation, 23.38° internal rotation, 6.76° extension, and 42.49° flexion in the non-dominant shoulder, and 39.45° adduction, 12.76° external rotation, 24.98° internal rotation, 11.86° extension, and 55° flexion in the dominant shoulder. In accordance with the literature, the extremity responsible for stabilization was found to require less RoM compared to the limb responsible for manipulation (49). It is thought that these results are closely related to the characteristics of the activities evaluated. In order to obtain more precise conclusions, studies that examine the bimanual activity variations, angular velocity and acceleration data other than functional RoMs are needed in more detail.

Most of studies in the literature, 'plane of elevation', 'elevation angle' and 'rotation angle' terms used to describe movement [2,8]. In addition, it is seen that it is difficult to compare the results in literature because of insufficiently explained experimental protocols and the results of studies which are influenced by the physical characteristics of the individuals and environmental variables. Therefore, in this study, environmental variables and the experimental protocol were standardized, and results were expressed in compliance with the clinical presentation. In conclusion, 9 different movements including bimanuel activities in the trunk and upper extremity functional RoMs were revealed. These results are thought to be guiding in follow-up of patients in the clinic and in technological product development processes (robotics, mechanical prosthesis etc.).

There are some limitations of this study. The scapula and finger kinematics were not analyzed. It is also known that scapula and finger movements are important for the activities used frequently in daily life. Our study sample was chosen from young people. It is considered that it is necessary to include older / younger populations in the researches in order to determine more comprehensive normative data of daily living activities. Because it is thought that the range of motion requirements of ADLs may be different within various age groups.

5. Conclusions

The results of this study showed that RoM requirements of nine different unilateral, bimanual asymmetrical and bilateral symmetrical activities. It is tought that these results will contribute to determine priority of task-spesific rehabilitation programs based patient's motor skill level, and to determine requirements of normative data for supportive technological rehabilitation approaches.

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Declaration of interest

None.

Author contributions

MD contribute to kinematic analysis of the nine ADLs. MeK contributed to analysis of data. MD, SAY, MuK, OU and EA contributed to the study design and plan. MD, GS, OOK and FA contributed to the interpretation of the date and creation of the manuscript. All authors confirmed and approved the final manuscript.

References

[1] A. de los Reyes-Guzmán, I. Dimbwadyo-Terrer, F. Trincado-Alonso, F. Monasterio-Huelin, D. Torricelli, A.J.C.B. Gil-Agudo, Quantitative assessment based on kinematic measures of functional impairments during upper extremity movements: a review, Clin. Biomech. Bristol Avon (Bristol, Avon) 29 (7) (2014) 719–727.
[2] A. Oosterwijk, M. Nieuwenhuis, C. van der Schans, L.J.Pt. Mouton, Shoulder and elbow range of motion for the performance of activities of daily living: a systematic review, practice 34 (7) (2018) 505–528.
[3] D. Fergusson, B. Hutton, A.J.C.O. Drodge, The epidemiology of major joint contractures: a systematic review of the literature, Clin. Orthop. Relat. Res. 456 (2007) 22–29.
[4] M. Klotz, L. Kost, F. Braatz, V. Ewerbeck, D. Heitzmann, S. Gantz, et al., Motion capture of the upper extremity during activities of daily living in patients with spastic hemiplegic cerebral palsy, Gait Posture 38 (1) (2013) 148–152.
[5] D. Magermans, E. Chadwick, H. Veeger, F.J.Cb.Van Der Helm, Requirements for upper extremity motions during activities of daily living, Clin. Biomech. (Bristol, Avon) 20 (6) (2005) 591–599.
[6] K. Petuskey, A. Bagley, E. Abdala, M.A. James, G.J.G. Rab, Upper extremity kinematics during functional activities: three-dimensional studies in a normal pediatric population, posture 25 (4) (2007) 573–579.
[7] A.J. Skalsky, C.M.J.P.M. McDonald, Prevention and management of limb contractures in neuromuscular diseases, Phys. Med. Rehabil. Clin. N. Am. 23 (3) (2012) 675–687.
[8] C.J. van Andel, N. Wolterbeek, C.A. Doorenbosch, D.H. Veeger, J.J.G. Harlaar, Complete 3D kinematics of upper extremity functional tasks, Posture 27 (1) (2008) 120–127.
[9] T. Willig, J. Bach, M. Rouffet, L. Krivickas, C.J.Ajopm. Maquet, Correlation of flexion contractures with upper extremity function and pain for spinal muscular atrophy and congenital myopathy patients, Rehabilitation 74 (1) (1995) 33–38.
[10] K. Korp, R. Richard, D.J.Jo.B.C. Hawkins, Refining the idiom "functional range of motion" related to burn recovery, Research 36 (3) (2015) e136–e145.
[11] M.A. Murphy, C. Willén, K.S.J.N. Sunnerhagen, Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass, Neurorehabil. Neural Repair. 25 (1) (2011) 71–80.
[12] J. Aizawa, T. Masuda, T. Koyama, K. Nakamaru, K. Isozaki, A. Okawa, et al., Three-dimensional motion of the upper extremity joints during various activities of daily living, J. Biomech. 43 (15) (2010) 2915–2922.
[13] S. Namdari, G. Yagnik, D.D. Ebaugh, S. Nagda, M.L. Ramsey, G.R. Williams Jret al., Defining functional shoulder range of motion for activities of daily living, J. Shoulder Elbow Surg. 21 (9) (2012) 1177–1183.
[14] S. Henmi, K. Yonenobu, T. Masatomi, K.J.Mr. Oda, A biomechanical study of activities of daily living using neck and upper limbs with an optical three-dimensional motion analysis system, Mod. Rheumatol. 16 (5) (2006) 289–293.
[15] P. Raiss, M. Maier, S. Wolf, O. Rettig, M. Loew, P.J.O.E. Kasten, 3D motion analysis of the upper extremities and its application in shoulder arthroplasty, 5 (1) (2010) 27.
[16] A. Murgia, P. Kyberd, T.J.G. Barnhill, The use of kinematic and parametric information to highlight lack of movement and compensation in the upper extremities during activities of daily living, Gait Posture 31 (3) (2010) 300–306.
[17] A. Sheikhzadeh, J. Yoon, V.J. Pinto, Y.W.J.Jo.S. Kwon, E. Surgery, Three-dimensional motion of the scapula and shoulder during activities of daily living, J. Shoulder Elbow Surg. 17 (6) (2008) 936–942.
[18] J. Lobo-Prat, J.M. Font-Llagunes, C. Gómez-Pérez, J. Medina-Casanovas, R.M.J.Cmib. Angulo-Barroso, New biomechanical model for clinical evaluation of the upper extremity motion in subjects with neurological disorders: an application case, Comput. Methods Biomech. Biomed. Eng. 17 (10) (2014) 1144–1156.
[19] R.J.Jon. Baker, Gait analysis methods in rehabilitation, J. Neuroeng. Rehabil. 3 (1) (2006) 4.

[20] M. Al-Amri, K. Nicholas, K. Button, V. Sparkes, L. Sheeran, J.L.J.S. Davies, Inertial measurement units for clinical movement analysis: reliability and concurrent validity, Sensors (Basel) 18 (3) (2018) 719.
[21] S. Patel, H. Park, P. Bonato, L. Chan, M.J.Jon. Rodgers, A review of wearable sensors and systems with application in rehabilitation, J. Neuroeng. Rehabil. 9 (1) (2012) 21.
[22] D. Steins, I. Sheret, H. Dawes, P. Esser, J.J.Job. Collett, A smart device inertial-sensing method for gait analysis, J. Biomech. 47 (15) (2014) 3780–3785.
[23] F.B. van Meulen, J. Reenalda, J.H. Buurke, P.H.J.Aobe. Veltink, Assessment of daily-life reaching performance after stroke, Ann. Biomed. Eng. 43 (2) (2015) 478–486.
[24] A. Ferrari, A.G. Cutti, P. Garofalo, M. Raggi, M. Heijboer, A. Cappello, et al., First in vivo assessment of "Outwalk": a novel protocol for clinical gait analysis based on inertial and magnetic sensors, Med. Biol. Eng. Comput. 48 (1) (2009) 1, https://doi.org/10.1007/s11517-009-0544-y.
[25] T. Seel, J. Raisch, T. Schauer, IMU-based joint angle measurement for gait analysis, Sensors (Basel). 14 (4) (2014) 6891 http://www.mdpi.com/1424-8220/14/4/6891.
[26] J.C. van den Noort, A. Ferrari, A.G. Cutti, J.G. Becher, J.J.M. Harlaar, B. Engineering, et al., Gait analysis in children with cerebral palsy via inertial and magnetic sensors, Med. Biol. Eng. Comput. 51 (4) (2013) 377–386, https://doi.org/10.1007/s11517-012-1006-5.
[27] A. Cuesta-Vargas, A. Galán-Mercant, J. Williams, The use of inertial sensors system for human motion analysis, Phys. Ther. Rev. (2010).
[28] H. Luinge, P. Veltink, Measuring orientation of human body segments using miniature gyroscopes and accelerometers, Med. Biol. Eng. Comput. (2005).
[29] X. Robert-Lachaine, H. Mecheri, C. Larue, A.J.M. Plamondon, Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis, Med. Biol. Eng. Comput. 55 (4) (2017) 609–619.
[30] J.-T. Zhang, A.C. Novak, B. Brouwer, Q.J.Pm. Li, Concurrent validation of Xsens MVN measurement of lower limb joint angular kinematics, Physiol Meas. 34 (8) (2013) N63.
[31] G. Wu, F.C.T. van der Helm, H.E.J. Veeger, M. Makhsous, P. Van Roy, C. Anglin, et al., ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part II: shoulder, elbow, wrist and hand, J. Biomech. 38 (5) (2005) 981–992 http://www.sciencedirect.com/science/article/pii/S002192900400301X.
[32] G. Brigstocke, A. Hearnden, C.A. Holt, G.J.Jo.H.S. Whatling, The functional range of movement of the human wrist, J. Hand Surg. 38 (5) (2013) 554–556.
[33] E. Inada, I. Saitoh, Y. Yu, D. Tomiyama, D. Murakami, Y. Takemoto, et al., Quantitative evaluation of toothbrush and arm-joint motion during tooth brushing, Clin. Oral Investig. 19 (6) (2015) 1451–1462.
[34] G.J.Jrm. Stucki, ICF linking rules: an update based on lessons learned, J. Rehabil. Med. 37 (37) (2005) 212–218.
[35] J. Robertson, A. Roby-Brami, The trunk as a part of the kinematic chain for reaching movements in healthy subjects and hemiparetic patients, Brain Res. (2011).
[36] L.H.C. Peeters, I.J.M. de Groot, A.C.H. Geurts, Trunk involvement in performing upper extremity activities while seated in neurological patients with a flaccid trunk – a review, Gait Posture 62 (2018) 46–55 http://www.sciencedirect.com/science/article/pii/S0966636218301103.
[37] B. Stansfield, S. Rooney, L. Brown, M. Kay, L. Spoettl, S. Shanmugam, Distal upper limb kinematics during functional everyday tasks, Gait Posture 61 (2018) 135–140 http://www.sciencedirect.com/science/article/pii/S0966636218300043.
[38] J. Karner, W. Reichenfelser, M.J.B.E. Gfoehler, Kinematic and kinetic analysis of human motion as design input for an upper extremity bracing system, 9 (1) (2012).
[39] S.L. Carey, M.J. Highsmith, M.E. Maitland, R.V.J.C.B. Dubey, Compensatory movements of transradial prosthesis users during common tasks, Clin. Biomech. (Bristol, Avon) 23 (9) (2008) 1128–1135.
[40] M. Masjedi, C. Lovell, G.R.J.Hms. Johnson, Comparison of range of motion and function of subjects with reverse anatomy Bayley–Walker shoulder replacement with those of normal subjects, Hum. Mov. Sci. 30 (6) (2011) 1062–1071.
[41] K. Kim, W.-K. Song, J. Lee, H.-Y. Lee, D.S. Park, B.-W. Ko, et al., Kinematic analysis of upper extremity movement during drinking in hemiplegic subjects, Clin. Biomech. 29 (3) (2014) 248–256.
[42] S.M. Waller, J.J.N. Whitall, Bilateral arm training: why and who benefits? NeuroRehabilitation 23 (1) (2008) 29–41.
[43] D.H. Gates, L.S. Walters, J. Cowley, J.M. Wilken, L. Resnik, Range of motion requirements for upper-limb activities of daily living, Am. J. Occup. Ther. 70 (1) (2016) 7001350010p1-7001350010p10.
[44] J. Bible, D. Biswas, C.P. Miller, P.G. Whang, J.N. Grauer, Normal functional range of motion of the cervical spine during 15 activities of daily living, J. Spinal Disord. Tech. (2010).
[45] J. Bible, D. Biswas, C.P. Miller, P.G. Whang, J.N. Grauer, Normal functional range of motion of the lumbar spine during 15 activities of daily living, J. Spinal Disord. Tech. (2010).