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Detection of the movement of the humerus during daily activity

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Abstract A new ambulatory technique for qualitative and quantitative movement analysis of the humerus is presented. 3D gyroscopes attached on the humerus were used to recognize the movement of the arm and to classify it as flexion, abduction and internal/external rotations. The method was first validated in a laboratory setting and then tested on 31 healthy volunteer subjects while carrying the ambulatory system during 8 h of their daily life. For each recording, the periods of sitting, standing and walking during daily activity were detected using an inertial sensor attached on the chest. During each period of daily activity the type of arm movement (flexion, abduction, internal/external rotation) its velocity and frequency (number of movement/hour) were estimated. The results showed that during the whole daily activity and for each activity (i.e. walking, sitting and walking) the frequency of internal/external rotation was significantly higher while the frequency of abduction was the lowest ($P < 0.009$). In spite of higher number of flexion, abduction and internal/external rotation in the dominant arm, we have not observed in our population a significant difference with the non-dominant arm, implying that in healthy subjects the arm dominance does not lie considerably on the number of movements. As expected, the frequency of the movement increased from sitting to standing and from standing to walking, while we provide a quantitative value of this change during daily activity. This study provides preliminary evidence that this system is a useful tool for objectively assessing upper-limb activity during daily activity. The results obtained with the healthy population could be used as control data to evaluate arm movement of patients with shoulder diseases during daily activity.

Keywords Outcome evaluation · Accelerometers and gyroscopes · Shoulder mobility · Ambulatory system

1 Introduction

Most quantitative approaches for shoulder movement analysis are performed in a laboratory setting where motion capture devices such as camera [9], electromagnetic [7], or electromyogram [6, 8] systems are used. Although very accurate and important for movement analysis their use is limited to the restricted volume of the laboratory. In order to quantify the movement that the subject can actually do during daily activity, it is useful to use an ambulatory device that can be carried by the subject during a whole day [1]. Long-term monitoring of shoulder movement (i.e. flexion, abduction and internal/external rotation) before and after intervention provides in this way objective outcomes for the evaluation of treatment. Such a movement monitoring can be performed using inertial sensors (e.g. accelerometers and gyroscope) attached on shoulder segments [3, 4]. However, there is no study currently about the actual number of shoulder movements during daily activities, even though these studies can provide an objective evaluation of shoulder disease and its treatment.

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There is a general agreement that patients with rotator cuff impingement, adhesive capsulitis or glenohumeral degenerative diseases have a diminished arm flexion, abduction or internal/external rotation. In spite of complex studies, a precise evaluation of the shoulder movement based on the estimation of the number of movements per hour in real life conditions is still missing.

The goal of this study was twofold: first, validating an algorithm for the detection of the humerus movement of the shoulder (flexion, abduction and internal/external rotations), and second to evaluate the effectiveness of this algorithm during long-term measurements. By validating such an approach, we should provide a clinical tool that can be used to assess the shoulder's function and to find objective scores for outcome evaluation of a shoulder pathology treatment.

2 Methods

2.1 Subjects and materials

A total of 31 healthy subjects (32 years old ± 8; 18 men, 13 women; 23 right handed, 8 left handed) were studied. Right or left handedness was established by a questionnaire. These data were used previously by Coley et al. [3, 4] in order to estimate the dominance of the arm and it position during daily activity. In order to show a clinical application of the proposed methods, one patient suffering from a rotator cuff disease implying a right shoulder supraspinatus rupture of 1 cm^2 (48 years old, right-handed) was studied. In this study two inertial modules with three miniature capacitive gyroscopes (Analog device, ADXRS 250, ±400 deg/s) were fixed by a patch on each dorsal side of the distal humerus and one module with 3D gyroscopes and three miniature accelerometers (Analog device, ADXL 210, ±5 g) on the thorax [2] (Fig. 1). The sensors on the humerus were placed in such a manner to be aligned with the axis of humerus in order to measure the anterior flexion–extension (pitch), abduction–adduction (yaw) and internal–external rotation (roll) of the shoulder, and the module fixed on the thorax was used for detecting daily activities (walking, sitting, standing) by using the method proposed by Najafi et al. [10, 11]. The signal from the sensors were amplified and low-pass filtered (cutoff frequency: 17 Hz) to remove any electronic noise and artifacts. The sensors and their conditioning electronics were packaged in a very small box (20 × 20 × 12 mm). All signals were digitized at 200 Hz sampling rate and recorded by two synchronized data loggers (Physilog®, BioAGM, CH) carried on the subject's waist [2].

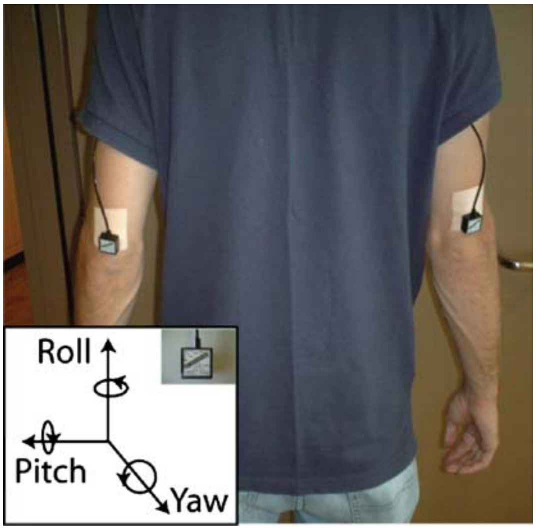

Fig. 1 Position of the inertial modules including 3D gyroscopes

2.2 Body posture detection

Body posture allocations (sitting and standing) as well as walking periods were detected by the trunk inertial module [10, 11]. The time of sit–stand (respectively stand–sit) transition was detected from the patterns of angular tilt obtained from the gyroscope. Pattern recognition of the vertical acceleration allowed classifying the transition and deciding if the subject was in a standing or a sitting position. A walking period was defined as an interval with at least three gait cycles. The walking state was identified by analyzing the vertical accelerometer every five-seconds. The difference between the right and the left shoulder activity is shown for each period corresponding to sitting, standing and walking.

2.3 Detection of the humerus movements

3D angular velocities of the humerus were used to detect the movement and its axis of rotation. The pitch, roll and yaw angular velocities were associated respectively with flexion/extension, internal/external rotation and abduction/adduction movement of the arm in agreement with ISB standardization proposal [13]. Figure 2 shows the three angular velocities recorded respectively for a flexion movement of 90°, an abduction of 90° and an internal/external rotation of 90°. During the flexion, the range of the pitch angular velocity was higher than the two other components (yaw and roll). Similar results can be observed for internal/external rotation (i.e. the range of the roll angular velocity was higher than yaw and pitch components) and for abduction (i.e. the range of the yaw angular velocity was higher than pitch and roll components).

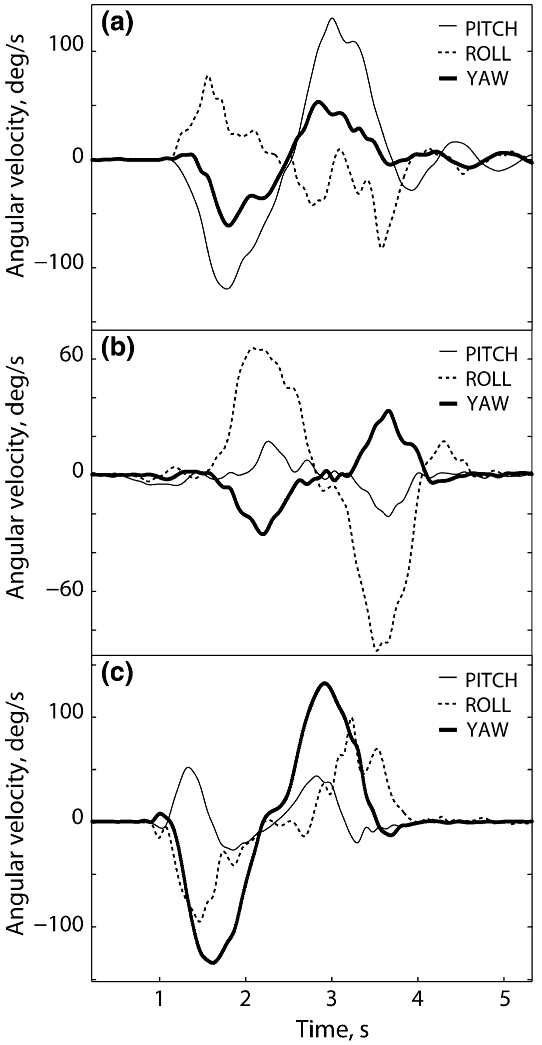

Fig. 2 Angular velocities (pitch, roll, yaw) detected by 3D gyroscope sensors for the flexion (**a**), the internal/external rotation (**b**) and the abduction (**c**)

To detect the shoulder movement, the absolute values of each component of angular velocity (pitch, roll, and yaw) was compared to a threshold (th). The shoulder was considered in movement if at least one component of angular velocity was higher than the th. The type of the movement (FE, AA, I.E) was estimated by considering the component of angular velocity with highest absolute angular velocity. If the highest angular velocity was pitch the movement was defined as a flexion–extension (FE). Similarly, if the highest absolute angular velocity belonged to yaw or roll, the movement was defined as abduction–adduction (AA) or internal/external rotation (I.E) respectively.

The threshold (th) was necessary to avoid the noise of the gyroscopes at rest and to decrease the false detections of the movement. The threshold (th) was adapted (adaptive threshold) every hour during the recording and was estimated for each subject and each humerus. To define th, we searched during each hour of recording all the positive peaks for each of the three angular velocities higher than 10°/s (almost still period of humerus). For each angular velocity, we calculated the average of the peaks. The threshold (th) was fixed to the minimum value of these averages.

2.4 Validation setup

To estimate the performance of the algorithm to correctly classify the type of the movement, the 31 subjects carried the system and were asked to perform at their desired velocity 2 flexions, 2 abductions and 2 internal/external rotations with both arms while in the hospital. For the flexion and abduction subjects started with the arm along the body and performed a 90° elevation while keeping the elbow unbent. The starting position of the internal/external rotation movement was with the upper-arm along the body and the elbow flexed at 90°. Subjects were asked to perform an external rotation of 90°. A physiotherapist validated the movements done by the subject. In case of a wrong movement, the physiotherapist asked the subject to perform the movement again. The sensitivity (defined as the ability of the system to correctly identify the true movement) and the specificity (defined as the ability of the system to not generate false detection) were estimated. The sensitivity and the specificity were calculated as follows

Sensitivity was defined as

$$\frac{\text{True positive(TP)}}{\text{True positive (TP) } + \text{False negative (FN)}} \times 100\% \qquad (1)$$

Specificity was defined as

$$\frac{\text{True negative(TN)}}{\text{True negative (TN) } + \text{ False positive (FP)}} \times 100\% \qquad (2)$$

For example, for the flexion movements the above parameters were defined as follow: the true positives were the numbers of true flexion detected by the algorithm. The false negatives were the numbers of undetected flexion. The true negatives were the numbers of other type of movement detected by the algorithm, which are not true flexion. The false positives were the numbers of false detection as flexion.

2.5 Long-term measurement

Each subject carried the ambulatory system during one day ($\sim$8 h) at home or wherever he/she went. At the end of recording, the data was transferred to the computer for further analysis, and then the following parameters were estimated

- The type of daily activity: sitting, standing and walking.
- The type of the movement: FE, AA and I.E.
- The frequency of each movement: the number of movements per hour recognized as flexion–extension (N_{FE}), abduction–adduction (N_{AA}) and internal/external rotation (N_{IE}). This frequency was estimated for all activity as well as for each type of daily activity.
- The frequency of each movement over three ranges of angular velocities: slow (less than 50 deg/s), medium (between 50 and 100 deg/s) and fast (higher than 100 deg/s).

By definition frequency is normalized by the duration of each activity, it could therefore be a better metric that the number of movements that change with the duration of each activity.

The Wilcoxon ranked sum test was used as a non-parametric hypothesis test to show if there were any significant differences (at a significance level of 5%) in the frequency of each movement.

3 Results

3.1 Validation

Table 1 summarizes the changes in sensitivity and specificity with the threshold obtained for different type of movement. Adaptive threshold provided excellent performances, while the minimum threshold (10 deg/s) corresponded to the worst cases. A fixed threshold of 33 deg/s, corresponding to the average of all adaptive thresholds during long-term recording, was not satisfying either.

Table 1 Specificity and sensitivity for the detection of the flexion, abduction and internal/external rotation

Threshold	Movement	TP	TN	FP	FN	Sensitivity (%)	Specificity (%)
10 deg/s	Flexion	31	123	7	34	47	95
	Abduction	24	102	28	41	37	78
	Int/ext rotation	56	81	49	9	86	62
33 deg/s	Flexion	41	122	8	24	63	94
	Abduction	36	108	22	29	55	83
	Int/ext rotation	61	107	23	4	94	82
Adaptive	Flexion	58	124	0	4	94	100
	Abduction	62	120	4	0	100	97
	Int/ext rotation	62	124	0	0	100	100

TP True positive, *TN* true negative, *FP* false positive, *FN* false negative

3.2 Long-term measurement

For each subject, walking, sitting and standing postures were recognized over a day (~8 h) and for each posture the frequency of each movement was estimated for each humerus (N_{FE}, N_{AA}, N_{IE}). Table 2 summarizes the value of the frequency over all activity by dividing the number of movement by the duration of measurement (~8 h). Table 3 reports the value of frequency for each posture, by

Table 2 Frequency (number per hour) of flexion (N_{FE}), abduction (N_{AA}) and internal/external rotation (N_{IE}) for all activities for the right handed subjects (r1 to r23) and left handed subjects (l1–l8) with their mean and standard deviation (SD)

Subject	N_{FE}		N_{AA}		N_{IE}	
	Right	Left	Right	Left	Right	Left
r1	157	121	73	47	272	259
r2	150	181	76	59	291	273
r3	129	105	44	35	209	168
r4	124	109	59	70	301	244
r5	87	95	54	40	251	188
r6	123	72	37	33	213	113
r7	136	189	90	56	298	274
r8	99	96	38	38	237	219
r9	131	119	36	35	185	165
r10	86	68	39	33	160	103
r11	165	154	68	57	309	213
r12	215	199	96	109	476	444
r13	161	122	69	87	308	306
r14	246	222	140	139	521	473
r15	210	175	81	102	406	388
r16	153	173	77	65	406	310
r17	134	139	66	53	311	283
r18	205	146	80	67	420	396
r19	252	287	152	103	492	476
r20	183	150	93	70	333	322
r21	210	229	112	114	534	503
r22	196	176	104	80	438	377
r23	234	224	87	97	539	491
Mean	165	154	77	69	344	304
SD	49	55	31	30	116	122
l1	156	209	86	112	325	342
l2	129	129	70	65	306	326
l3	206	163	83	90	396	407
l4	141	146	68	95	270	270
l5	200	169	89	94	388	408
l6	79	93	47	50	190	198
l7	245	265	98	141	360	376
l8	201	244	99	107	388	406
Mean	170	177	80	94	328	342
SD	53	58	17	28	71	75

Table 3 Frequency of the movement N_{FE}, N_{AA} and N_{IE} for the right and left handed subjects

Subject	Walk						Sit						Stand					
	N_{FE} right	Left	N_{AA} right	Left	$N_{\mathrm{IE\ right}}$	Left	N_{FE} right	Left	N_{AA} right	Left	N_{IE} right	Left	N_{FE} right	Left	N_{AA} right	Left	N_{IE} right	Left
r1	464	280	250	175	795	822	113	89	52	25	210	178	142	122	60	45	231	234
r2	349	493	206	145	708	693	72	92	29	27	133	119	132	133	66	52	255	236
r3	378	568	209	127	745	779	97	47	19	22	129	83	143	119	57	41	253	204
r4	380	373	184	288	747	740	67	52	35	30	199	119	103	89	42	47	246	226
r5	332	450	283	180	799	807	34	27	13	16	129	60	70	65	33	23	205	148
r6	723	668	231	296	919	863	82	31	27	16	156	55	114	75	25	30	219	130
r7	349	581	256	140	765	816	83	98	43	27	152	120	104	139	78	52	267	239
r8	396	244	175	137	697	758	75	80	27	33	213	187	85	89	31	28	182	170
r9	712	688	261	204	856	872	47	46	11	14	91	67	115	96	24	27	163	140
r10	496	541	341	343	805	812	70	34	25	11	111	42	41	30	10	9	101	52
r11	590	607	251	260	858	759	94	80	43	34	206	112	160	149	56	39	303	224
r12	440	426	204	288	837	841	88	100	31	35	259	203	187	153	88	83	403	388
r13	498	396	201	318	871	898	95	66	44	39	185	170	163	127	66	96	321	332
r14	424	440	265	269	783	808	136	101	60	69	301	232	165	140	93	88	378	331
r15	484	389	207	233	778	751	99	87	31	37	224	193	131	111	49	73	286	284
r16	531	607	252	184	830	883	87	108	40	34	301	201	140	144	76	68	386	285
r17	530	564	254	184	822	863	46	39	21	18	142	109	96	103	51	42	275	243
r18	361	261	125	104	716	680	90	63	34	29	203	184	131	91	57	48	269	254
r19	544	597	272	216	878	889	102	117	80	46	251	209	188	218	120	77	389	378
r20	604	559	265	219	878	841	79	58	38	32	179	165	132	99	82	52	261	265
r21	440	471	239	211	862	886	119	133	61	58	356	283	156	171	84	93	432	412
r22	412	434	242	184	843	793	124	96	60	49	266	199	182	166	99	73	440	398
r23	416	466	160	199	877	900	109	90	31	25	262	196	173	155	66	71	415	366
Mean	472	483	232	213	812	815	87	75	37	32	202	152	133	121	61	55	290	258
SD	109	124	46	65	61	64	25	30	17	14	68	64	38	41	27	24	92	95
l1	560	591	290	281	827	825	118	188	53	102	276	315	165	232	98	130	382	399
l2	393	387	178	189	785	775	81	84	47	41	200	220	113	108	66	59	294	319
l3	512	439	237	262	853	789	52	38	21	19	117	123	164	123	57	64	339	369
l4	584	657	325	332	866	876	93	101	37	82	194	212	128	118	64	76	274	250
l5	546	403	193	229	860	886	95	98	48	41	194	217	137	120	69	73	304	317
l6	236	379	210	198	687	792	43	44	21	25	101	96	126	120	56	67	260	260
l7	543	544	198	195	721	693	89	174	47	77	184	241	218	212	87	149	319	327
l8	563	589	309	205	859	822	81	93	37	47	168	216	162	225	74	107	360	362
Mean	492	499	242	236	807	807	82	103	39	54	179	205	152	157	72	90	316	325
SD	119	109	57	51	70	61	24	54	12	30	54	68	33	55	15	34	42	52

dividing the number of movement in each posture by the total time of this posture during measurement. The average of the frequency was higher for the right humerus (flexion right: 165; flexion left: 154; abduction right: 77; abduction left: 69; internal/external rotation right: 344; internal/external rotation left: 304) for the right handed subjects ($n = 23$). While for the left handed subjects, the average of the frequency was higher for the left humerus ($n = 8$) (flexion right: 170; flexion left: 177; abduction right: 80; abduction left: 94; internal/external rotation right: 328; internal/external rotation left: 342) (Table 3). However, statistical tests showed that the dominant shoulder and the non-dominant shoulder had no significant difference ($P > 0.1$) for the frequency of flexions (N_{FE}), abductions (N_{AA}) and internal/external rotations (N_{IE}) in the sitting and standing posture (Table 2). Moreover, there was no significant difference ($P > 0.3$) between the dominant and non-dominant shoulder in the gait.

The frequency of the movement was significantly higher for walking compared to sitting and standing and significantly lower in sitting compared to standing ($P < 0.008$). For all postures, as well as during the whole daily activity,

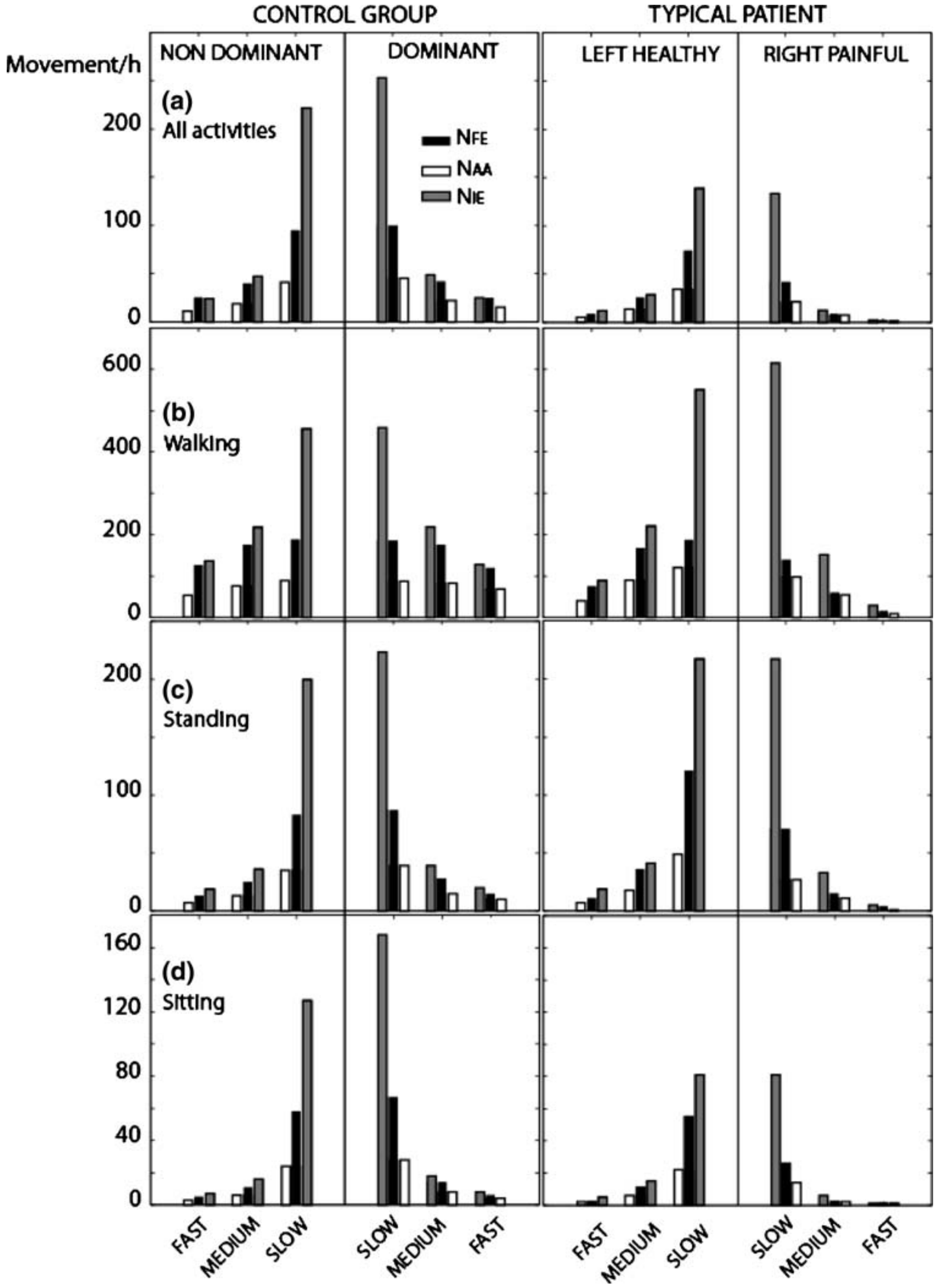

Fig. 3 Distribution of the movements (frequency vs. range of angular velocities values) for the control group and for a right-handed patient suffering from rotator cuff disease in the right shoulder. **a** All activities **b** walking, **c** standing, **d** sitting. Slow (up to 50 deg/s), medium (between 50 and 100 deg/s) and fast (more than 100 deg/s)

we found a significantly higher frequency of movement in internal/external rotation and the lowest frequency of movement in abduction ($P < 0.009$).

3.3 The change of humerus velocity due to pain

Another aspect, which could be studied in shoulder pathology is the change of humerus velocity due to pain. To highlight this point we have plotted in Fig. 3 for all control subjects the distribution of each movement per hour in three ranges of angular velocity: slow (up to 50 deg/s), medium (between 50 deg/s and 100 deg/s) and fast (more than 100 deg/s). For comparison we have performed a long-term recording with right-handed patient suffering from a rotator cuff tear in the right shoulder.

4 Discussion

In this study, an ambulatory system was proposed to evaluate the mobility of the shoulder during daily physical activity. The method used the speed of rotation of the humerus and not the orientation of the humerus, avoiding in this way any noise and drift due to time integration of the gyroscope signals to find angles [5]. The performance of the method to detect the movement and classify the movement as FE, AA and IE lies on the adequate choice of the threshold (th). By using an adaptive threshold we provided a better performance since th was modified based on the amplitude of angular velocity in each window of 1 h. We also evaluated the change in th during the validation setup and for the long-term measurement of each subject. We noticed that the mean th (over 8 h and all subjects) was different for the validation phase ($\mathrm{th} = 52 \pm 7$ deg/s) where the movement was imposed and the long-term measurement ($\mathrm{th} = 33 \pm 3$ deg/s) where the movement was spontaneous. To show the efficacy of the adaptive threshold, we calculated the specificity and the sensitivity in the validation phase with a fixed threshold of 33 deg/s obtained from the long-term measurement. The sensitivities and specificities obtained were lower than those with the adaptive threshold.

Based on 3D gyroscopes on both humeri, our method has not only qualified the type of the movement but also quantified the frequency and the speed of the movement in FE, AA and I.E and their change between dominant and non-dominant shoulder during daily activity. Although in our healthy population the dominant shoulder has a higher frequency of the movement compared to non-dominant side, we have not observed a significant level of difference ($P > 0.1$). These results would also imply that in healthy subjects the arm predominance does not lie considerably on the number of movements in the arm. If we compare this finding with our recent results, where the dominant and non-dominant arms have significantly different intensity during movement [3], we can conclude that the frequency should be estimated in terms of the velocity of the movement as proposed in Sect. 2.5 and shown in Fig. 3.

We observed that the frequency of the movement increased from sitting to standing and from standing to walking. Although this would be expected, since we have more activities during standing and walking compared to sitting, the present study provided a quantitative value of these changes. In addition, in daily activities the most common movement was the internal/external rotation and the less frequent one was the abduction. While the movement of flexion was important during the gait for example, the movements of internal/external rotation were performed during all daily tasks like working in an office, cleaning a table etc. Our proposed technique could be useful to determine daily physical activities which require the most flexion, abduction or internal/external rotations.

As far as our clinical case is concerned, we can conclude that our right-handed patient with a painful right shoulder performed more movements with the left shoulder (non-dominant) than the right shoulder (dominant) during his daily activities (Fig. 3). The frequency of the movement distribution in the healthy non-dominant shoulder is close to the non-dominant shoulder of the control population. The frequency of the movement and the velocity distribution for the patient is higher for the left healthy shoulder than the right painful shoulder. We can expect that this tendency should be logically reversed after the surgery of the shoulder and recovery. Moreover, we can observe more difference in medium and fast movement than slow movement. This again assumes an increase of the frequency of the faster movement after surgery. Futures studies with higher number of patients are needed to confirm these hypotheses and show the shoulder function evolution after surgery.

A potential extrinsic confounding parameter could be the external charge (such as a bag or a suitcase) that the subject can carry during his daily activity with his arm. For example, it is not possible with the proposed method to determine whether a subject is performing ordinary walking or carrying a bag while walking. We can expect that by carrying a bag, the number of flexion will decrease and appears like a disease. Calibrating the ordinary walking of a subject at the beginning of a measurement period or using electromyogram recordings might be a solution. A method which is able to give 3D angles during the daily activity or the intensity of the movement will be complementary to this study. Indeed, the addition of the angles value or the power of the movement with the type of the rotation could illustrate more difference between the left and right shoulder.

5 Conclusion

Based on the shoulder kinematics, we were able to find the numbers of flexions, abductions and internal/external rotations of the humerus during daily activity for a healthy population. Our proposed system appears especially promising for long-term monitoring: the sensors have low power consumption (17 mA) and with standard batteries the system allows one to record up to 8 h on a memory of 512 MBytes. Monitoring the subjects in their usual environment with minimal interference is therefore possible in contrast with other systems that require a laboratory setting. These results were very encouraging for future evaluation of patients with shoulder injuries. This study will be also very helpful to simulate the performance of the new design of shoulder prosthesis and implants (in laboratory or numerically) because it can provide the actual shoulder movement during daily activity [12].

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