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Title
Learning and Identification of human upper-limb muscle synergies in daily-life tasks with autoencoders

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Summary
As a pilot study, we present 1)a database that includes 30 daily-life table-top tasks, which were selected within the SoftPro project, and 2)a novel autoencoder-based muscle synergy identification method, whose results indicate an association between synergy space dimensionality and task complexity.

Introduction
Human motor control underlies all human activities, such as reaching and grasping an object. Although the task space seems simple and low-dimensional, the number of actually involved actuators, i.e., muscles, is significantly higher than the effective degrees of freedom. Due to this anatomical redundancy, muscles shall work in a synergistic manner which leads to a low-dimensional synergy space and ergo a synergy-based control [1,2]. In fact, several studies have focused on human upper-limb muscle synergies either of only local muscles [3], or in isometric tasks [1][3], or in specifically designed tasks [4].
In the present work, instead of such specific conditions, more general and daily-life cases are considered and analyzed. Systematic experiments are conducted in order to gather the relevant multi-joint motion trajectories and multi-muscle surface electromyograms (sEMG), as well as identify task-dependent muscle synergies.

Methods
In the experimental series we report, one healthy male human subject – no neuromuscular disorder known – had volunteered, where he performed the 30 daily-life table-top tasks involving upper-limb movements. The selection of the analyzed tasks was developed within the SoftPro consortium (European Union’s Horizon 2020 No 688857). During the experiment, the

sEMG of 27 shoulder, arm, and forearm muscles/subregions were recorded with a Refa system (TMSi, Netherland), meanwhile, the upper-limb kinematics were captured with a Vicon MXT10s (Vicon Motion Systems Ltd, UK).

After the recorded sEMG signals are denoised by a bandpass filter [5], the muscle activations u are extracted from that via full-wave rectification and a lowpass filter [6,7], and are normalized to the maximal values for each muscle. In order to identify muscle synergies y from u, stacked autoencoders are applied, which reduce the 27-dimensional u to task-dependent lower-dimensional spaces y^taskn # R^K, where K # 27.

Results

For upper-limb muscle synergies, a 5-D space in a general sense was reported in [4]; this indicates that a task-dependent synergy space shall be even lower-dimensional. Therefore, different dimensionalities (K=4;3;2) have been chosen and are evaluated regarding the reconstruction errors #.

As illustrated in the figure, K=3 can be assumed for Tasks 1 – 10. This computational result agrees with the considered intransitive tasks where upper-limb end-effector orientation can be neglected, i.e., translation dominates. However, Tasks 3 & 6 suggest otherwise because fist (finger muscles) and hand wave (wrist muscles) are involved, respectively.

The reconstruction errors for the transitive Tasks 11 – 20, where reach and grasp occur often, suggest K=4. This matches the stronger involvement of finger motion and force exertion, and is comparable with Task 3. Furthermore, the difference between Tasks 1 – 10 and Tasks 11 – 20 suggests that a grasp is a strongly coordinated motion (1-D). One may notice #>0.01 for Tasks 13, 14 & 20, which are caused by a long lasting (Task 13) and a higher (Task 14 & 20) force exertion and suggest K>4 shall be applied in such cases.

For Tasks 21 – 30, one can see the similarities to the previous tasks. For instance, it suggests – based on reconstruction errors – K>4 for Tasks 21, 22 & 30, which involve a long lasting force exertion as in Task 13. And for the remaining tasks, K=4 is suggested, and they involve reach and grasp, similar to Tasks 11 – 20.

Conclusion

In the present preliminary work, we focused on the synergies among human upper-limb muscles. For this purpose, we firstly established a database of motion trajectories and sEMG, which covers all upper-limb joints and 27 measurable muscles/subregions and includes 30 daily-life table-top tasks. Although this database currently includes only one subject, it will be extended to multiple subjects in the near future.

With this database, we evaluated sEMG by means of the state-of-the-art Machine Learning technique autoencoders in terms of task-dependent synergy spaces, and found that the dimensionality of synergy space relates to the movement categories, i.e.,

- For a simple reaching movement, a 3-D synergy space is sufficient to describe a specific task.
- For reaching and grasping movements, where only a small amount of work shall be done, 4-D synergy spaces seem appropriate.
- For a reach and grasp movement which requires a greater amount of work, a meaningful synergy space shall possess higher dimensionality (K>4).

Although the preliminary results are limited to one subject only at the moment, the present work is considered as pilot study in establishing an experiment database and automatic identification of muscle synergies by learning via autoencoders. Future work will include more subjects, and the proposed autoencoder-based method of muscle synergy identification will be extended. Furthermore, the joint/kinematic synergies will be addressed as well.

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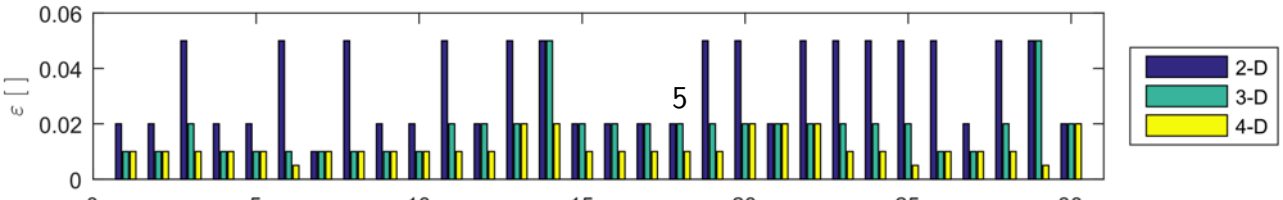
	#	Movement
Intransitive	1	OK gesture (lift the hand from the table)
	2	Thumb down (lift the hand from the table and extend the arm along sagittal plane)
	3	Exultation (extend the arm up in the air and keep it in with closed fist)
	4	Hitchhiking (extend the arm along frontal plane, laterally, parallel to the floor, with extended elbow, closed fist, extended thumb)
	5	Block out sun from face (with open hand, touch the face with the palm and cover the eyes)
	6	Greet (with open hand, first on the right side, move wrist) (3 times)
	7	Military salute (with lifted elbow)
	8	Stop gesture (extend the arm along sagittal plane, parallel to the floor, with extended elbow, open palm)
	9	Pointing (with index finger) of something straight ahead (with outstretched arm)
	10	Silence gesture (bring the index finger, with the remainder of hand closed, on the lips)
Transitive	11	Reach and grasp a small suitcase (placed along frontal plane) from the handle, lift it and place it on the floor (close to the stool, along sagittal plane)
	12	Reach and grasp a glass, drink for 3 seconds and place it in the initial position
	13	Reach and grasp a phone receiver (placed along sagittal plane), carry it to own ear for 3 seconds and place it in the initial position
	14	Reach and grasp a book (placed overhead on a shelf along own sagittal plane), put it on the table and open it (from right side to left side, 2 fingers + thumb)
	15	Reach and grasp a small cup from the handle (2 fingers + thumb), drink for 3 seconds and place it in the initial position
	16	Reach and grasp an apple, mimic biting and put it in the initial position
	17	Reach and grasp a hat (placed on the right side of the table) from its top and place it on own head
	18	Reach and grasp a cup from its top, lift it and put it on the left side of the table
	19	Receive a tray from someone (straight ahead, with open hand, extend the arm) and put it in the middle of the table
	20	Reach and grasp a key in a lock (vertical axis), extract it from the lock and put it on the left side of the table
Tool-mediated	21	Reach and grasp a bottle, pour water into a glass for 3 seconds and put the bottle in the initial position
	22	Reach and grasp a smartphone (placed in front of the subject, in the middle of the table), unlock it, dial a number, and place it back
	23	Reach and grasp a toothbrush (placed along sagittal plane), brush teeth (horizontal axis, one time on left side one time on right side) and put the toothbrush inside a cylindrical holder (placed on the right side of the table, vertical axis)
	24	Reach and grasp a laptop and open the laptop (without changing its position) (4 fingers + thumb)
	25	Reach and grasp a pen (placed on the right side of the table, along own sagittal plane) (2 fingers + thumb) and draw a vertical line on the table (from the top to the bottom)
	26	Reach and grasp a pencil (placed along own frontal plane) (3 fingers + thumb) and put it inside a squared pencil holder (placed on the left side of the table, horizontal axis)
	27	Reach and grasp a tea bag in a cup (1 finger + thumb), remove it from the cup and place it on the table on the right side of the table
	28	Reach and grasp (whole hand) a door handle, turn it clockwise and counterclockwise, and open the door (extend the arm and release the door handle)
	29	Reach and grasp a tennis ball (with fingertips) and place it in a basket placed on the floor (close to the stool)
	30	Reach and grasp a cap (2 fingers + thumb) of a bottle (held by left hand), unscrew it and place it overhead on a shelf



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