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Short Report

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Consideration and analysis for attachment position of supernumerary robotic limbs

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Abstract

The supernumerary robotic limbs(SRLs) is a new type of wearable robot that assists the operator with additional robotic limbs and allows the operator to perform multiple tasks simultaneously. Due to the SRLs has various combinations of robotic limb and attachment positions, and there is insufficient discussion on the influence of different wear positions on the SRLs. Therefore, this paper improved the evaluation indexes from previous studies and presents an experimental evaluation of the performance of indexes between the human and SRLs. This paper analyzed the 5 different positions based on the improved evaluation indexes, 2 optimal positions are found with the simulation experiment. Then the two design factors to improve the performance of evaluation indexes are discussed. The evaluation indexes can be utilized as a design parameter for evaluating human-robot interactions of SRLs.

Keywords: Wearable robot, Supernumerary robotic limbs, Workspace, Evaluation indexes

1 Introduction

Wearable robots have an important role in assisting human working or daily living. Supernumerary robotic limbs(SRLs) is a new type of wearable robot, which replaces the human natural limb to augmented human ability via the robotic limbs[25]. Different from the exoskeletons and traditional wearable robots, the SRLs designed to assist human with additional robotic limbs attached to the human body[11]. Therefore, the concept design of SRLs is different from the conventional wearable robot especially the wear position, size, and safety of SRLs.

In previous research, the researchers developed various types of SRLs according to the different tasks performed. Depending on the application scenario, SRLs have various design functions and also have multiple attachment locations[14]. For the positioning and lifting objects function, Davenport et al.[5, 15] designed 6 degrees of freedom(DOF) SRLs that is placed around the iliac crest. Kojima et al.[12, 13] designed SRLs named Assist Oriented Arm(AOA), which brace on the user's waist and have 4 DOF. Sasaki et al.[21] designed the metalimbs which are mounted on the user's back. Vatsal et al. [24]developed forearm-mounted SRLs for grasping objects. Ding et al.[6] proposed SRLs, named xLimb, that are

mounted on the wearer's upper arm and it can feature multiple functions of both storability and extendibility without obstruction to users. For balance assistance function, Parietti et al.[20] presented SRLs consist of two robotic legs, which have 3 DOF each other and worn by a backpack-like harness. Gonzalez et al.[8] designed the Extra Robotic Legs(XRL) system that is worn by the operator's back and reduces the payload. For overhead support function, Bonilla et al.[2] developed 5 DOF SRLs that is worn on the shoulders. Shin et al.[22] designed 3 DOF SRLs that is mounted on the user's shoulders and assist worker holding objects at the ceiling. Luo et al.[16] proposed back-mounted SRLs for overhead ceiling tasks. Summarized the representative SRLs, there are multiple combination approaches of the SRLs and user. And the SRLs' attachment locations are not unique in similar application scenarios.

In the aforementioned works, researchers proposed the many wearable positions of human body. These locations are selected because they are convenient for wear and they are minimum interference with human natural limbs. Due to the SRLs is closer to the human body than collaborative robots, the discussion on the safety and operation efficiency of SRLs is also essential. The different wear positions of SRLs is directly impacted the human-robot interaction includes safety and work efficiency. However, there are few studies discuss the performance of different attachment positions of SRLs in same task. Therefore, this paper aims at providing a detailed analysis and discussion of the function performance of the SRLs on the human body with different locations.

The structure of this paper is the following. In section 2 the related works and the performance indexes is described. In section 3 the analysis method and the simulation experiment parameters are reported. In section 4 reported and analyzed the simulation result. In section 5 this paper discussed the design factors and evaluation indexes. In section 6 this paper reported the conclusions and future works.

2 Preliminaries

2.1 Related works

There are some discussions about the attachment location of SRLs. Ciullo et al.[4]proposed arm-mounted SRLs for rehabilitation and evaluated the possible wear positions of the SRLs. They exploring 16 different positions and found the two optimal locations via the multi-variable Pareto analysis. This work has not considered the mass property of the system during the analytical analysis, so the optimal position is not suitable for patients with muscular disabilities. Nakabayashi et al.[17] evaluated the length and the wear location of SRLs. They proposed three evaluation indexes includes workspace extensiveness, cooperativeness, and invasiveness. They quantitatively evaluated the human-robot cooperativeness via these indexes. Moreover, these indexes also can evaluate collision safety[18]. However, this work only analysis one type of task scenario that causes the main workspace of human is special. And the analysis result is not suitable for multiple application scenarios, such as overhead support tasks. Therefore, this paper presented an analysis method for the general application scenario based on the evaluation indexes.

2.2 Improved performance indexes

Nakabayashi proposed evaluation indexes were defined according to the calculations of the common domain of the human workspace and the robot arm workspace[17]. It only considers the interference of robotic limbs to human natural hands. However, the human natural limbs would also interfere with the SRLs. Therefore, this paper improves the evaluation indexes as shown in Fig.1.

The workspace cooperativeness describes the range of areas where SRLs and users work together, it also reflects the efficiency of the SRLs working with humans. The higher workspace cooperativeness shows that the SRLs can meet the requirement of more collaborative tasks. The workspace extensiveness describes the extended area range of SRLs to the user's reachable space, it represents the SRLs the augment ability of SRLs to human. The higher workspace extensiveness reflect that SRLs can better adapt to the tasks beyond the reachable area of human. The

Fig. 1 Venn diagram of the SRLs and operator workspace

workspace invasiveness describes the range of possible collisions between SRLs and users during the operating, the lower workspace Invasiveness represents that SRLs have higher safety and reliability during the cooperative operating. And the each workspace are defined as follows.

$$V_c = V_{oh} \cap V_{sh} \quad (1)$$

$$V_e = V_{sh} - V_c \quad (2)$$

$$V_i = V_c - V_m + (V_m \cap V_{sa}) \quad (3)$$

Where, V_c is the cooperative workspace, V_e is the extensive workspace, V_i is the invasive workspace, V_{sh} is the SRLs hand workspace, V_{sa} is the SRLs arm workspace, V_{oh} is the operator hand workspace, V_m is the Main workspace.

The evaluation indexes are defined according to the calculation of the common domain of the SRLs' workspace and human workspace. The each evaluation indexes are defined as follows.

$$R_e = \frac{V_e}{V_{oh}} \quad (4)$$

$$R_c = \frac{V_c}{V_{oh}} \quad (5)$$

$$R_s = \frac{V_c - V_i}{V_c} \quad (6)$$

Where, R_e is the rate of workspace extensiveness, R_c is the rate of workspace cooperativeness, R_s represent the ratio of safety.

3 Methods

3.1 The workspace analysis

3.1.1 The human workspace base on the ergonomics

The human workspace is defined as shown in Fig. 2. The workspace are calculated by using the computer-aided design (CAD). The human workspace is proposed based on the ICF (international classification of functioning, disability, and health)[19]. The human workspace is the reachable area of humans and is suitable for the majority of tasks such as assembly tasks, carry tasks, and grasping tasks. The main workspace is the overlap volume of left-hand trajectory and right-hand trajectory, it represents the cooperative operating range of the human with two hands. The size of human workspace is defined as the data of human natural limbs according to the international standard ISO-7250-1:2008[9] and ISO/TR 7250-2:2010[7], and the data as shown in the Table 1. In order to adapt to the changes of individual differences, the simulated human size is the measurement 95 percentile of males in this paper.

3.1.2 The configuration and workspace of SRLs

According to the neuroscience research results[1, 3, 23], the robotic limb is anatomically similar to the natural hands and aligned in an anatomically similar fashion can reduce the cognitive load of operator[10]. According to the result of the questionnaires about the ideal SRLs, most participants preferred the length of SRLs to be as long or

Table 1 The statistical summary on human body size

Measurement Items (mm)	Percentage of Male (18–60 Years)					Percentage of Female (18–55 Years)				
	1	5	50	95	99	1	5	50	95	99
Body height	1543	1583	1678	1775	1814	1449	1484	1570	1659	1697
Upper arm length	279	289	313	338	349	252	262	284	308	319
Forearm length	206	216	237	258	268	185	193	213	234	242
Elbow height	933	960	1031	1102	1136	861	889	953	1020	1049
Shoulder height	1246	1282	1369	1460	1499	1151	1182	1263	1350	1384
Iliac spine height	814	842	912	982	1019	748	774	836	901	930
Shoulder breadth	362	374	401	432	444	326	335	358	383	397
Shoulder bideltoid breadth	409	423	457	500	521	366	377	405	444	468
Hip breadth	297	308	332	359	374	296	304	330	360	375
Wall-acromion distance	60	72	95	119	130	55	64	86	109	118
Grip reach; forward reach	611	635	693	750	773	565	588	635	690	713

Fig. 2 The diagram of human workspace

longer as their own arm[6]. This paper thus design the robotic limbs of SRLs has 7 degrees of freedom(DOF), and the joint configuration is similar to the human natural limb as shown in Fig. 3.

The shoulder and wrist joint has 3 rotational DOFs respectively includes x -pitch, y -roll, and z -yaw, and the elbow has one rotational DOF with x -pitch. The length of robotic limb is also same

Fig. 3 Size and structure diagram of SRLs

as the simulation human size, and the Denavit-Hartenberg (D-H)parameters of SRLs as shown in Table 2. The motion range of each joint is defined according to the motion range of human natural limbs. Then the SRLs' workspace is calculated via the Matlab robotics toolbox, the simulation result as shown in Fig. 4.

3.2 Candidate attachment positions of SRLs

In this analysis, the candidate attachment positions are proposed as shown in Fig.5. These locations are considered securing positions for a robotic limb that does not interfere with the

Table 2 Standard D-H parameter of SRLs

i	a_i (mm)	α_i (rad)	d_i (mm)	θ_i (rad)
1	0	$-\pi/2$	0	$\theta_1 \in [-\pi/6, 3\pi/4]$
2	0	$\pi/2$	0	$\theta_2 \in [-5\pi/6, \pi/2]$
3	0	$-\pi/2$	338	$\theta_3 \in [-4\pi/9, \pi/2]$
4	0	$\pi/2$	0	$\theta_4 \in [0, 5\pi/6]$
5	0	$-\pi/2$	258	$\theta_5 \in [0, \pi]$
6	0	$\pi/2$	0	$\theta_6 \in [-\pi/9, \pi/6]$
7	0	0	35	$\theta_7 \in [-4\pi/9, 7\pi/18]$

Fig. 4 The workspace of SRLs

movement of either hands or feet. The positions are classified into two types: one is distributed on the vertical axis of the human body includes head top(HDT) and abdomen(ABD), another is symmetry points include right shoulder above(RSA) and right shoulder side(RSS), right waist side(RWS) and left shoulder above(LSA), left shoulder side(LSS) and left waist side(LWS) are a set of symmetric points respectively. And the location of these points are defined according to the anthropometric dimension data of an average adult person, the data as shown in Table 1.

The same relative location between the human limb and the SRLs, when the robotic limb is secure on the symmetrical points. Therefore, each set of symmetrical points only needs to select one of them. In this analysis, the point LSA, LSS, and LWS is selected to analyze the performance of the evaluation indexes.

In this paper, the performance of evaluation indexes with different attachment positions via calculate the volume change of common workspace. The Fig. 6 shows an example overview

Fig. 5 Attachment position of the SRLs

of the common domain calculation for the human workspace and SRLs workspace.

Fig. 6 Calculation overview of the workspace(secure on the point LWS)

4 Results

The performance result of evaluation indexes with different positions as shown in Fig.7. The SRLs secure on the position LSS and LSA have higher workspace cooperativeness than other positions, and represent they have better performance of cooperating operate with human hands. The SRLs secure on the position ABD has the highest extensiveness workspace, and SRLs have better performance of expandability of human natural upper limbs. The attachment position LSA has the lowest workspace safety, and the SRLs secure on the

LSA have a high risk of collision between human upper limbs and robotic limbs.

Fig. 7 The performance of evaluation indexes of the different positions with single robotic limb

In these attachment positions, there is a negative correlation between cooperativeness and extensiveness. The attachment position is determined by the functional requirements of the task. For example, the assist in human holding or assembly task, this paper suggests SRLs secure on the LSA or LSS because of the high cooperative requirement. And another example such as putting away objects outside the operator's reach requires high extensiveness, and the SRLs maybe have better performance when secure on the position ABD. It shows that the expansibility and cooperative ability of SRLs need to be balanced in the design stage.

Moreover, the location of attachment positions is analyzed, The position ABD is the farthest from the shoulder and has the lowest cooperativeness, the LSS is the nearest from the shoulder and has high cooperativeness. It reflects a positive correlation between the workspace cooperativeness and the distance from the shoulder. This is because when SRLs brace on the shoulder, there is a large overlap between the robot workspace and the human workspace cause the high workspace cooperativeness. When the SRLs brace on the ABD or LWS, the majority area of SRLs' workspace is beyond the operator's reachable workspace, and causes the high workspace extensiveness, as shown in Fig. 8.

However, in some special application scenarios, the wearable position is constrained such as sitting

Fig. 8 The cooperativeness and extensiveness workspace

state operating. The shoulder is the ideal attachment position in this task. Meanwhile, the SRLs are required to extend the operating range. The length of robotic limbs may improve the extensiveness workspace. This paper will discuss the design factors that improve the performance of the evaluation indexes.

5 Discussion

5.1 The length factor of robotic limb

The length of the robotic limb can be related to the evaluation indexes, because the length can improve the range of the robot workspace. Therefore, the five different magnification lengths of robotic limbs that increment 0.25 from 1 time to 2 times are set based on the size of the human upper limb (Fig. 2). This paper analyzed the performance of evaluation indexes with different lengths, the result as shown in Fig. 9.

Compare the results of different lengths with the same attachment position, there is a positive correlation between the extensiveness workspace and robotic limb length. And the longer-length robotic limb also improves the workspace cooperativeness. However, when the robotic limb is 1.75 times or over longer than human upper limbs, the workspace cooperativeness of position HDT,

Fig. 9 The performance of evaluation indexes of the different positions with variable length robotic limbs

LSA, and LSS have a downward trend. And the long robotic limb would reduce the safety of SRLs, when the length of SRLs is longer than the human upper limb, it will have low workspace safety except for the position LSA.

Compare the results of the same lengths with the different attachment positions, the workspace extensiveness would not be affected by the attachment position, when the length of SRLs is 1.5 times longer than human upper limbs. And the SRLs will have similar workspace cooperativeness when the length is over 1.75 times longer than human upper limbs. Meanwhile, the workspace safety will be reduced in any attachment position when the robotic limb is longer than human limbs. Moreover, the long robotic limbs would increase the mass of the SRLs and reduce the comfort level of SRLs. Based on the above analysis, this paper thus suggests the length of the robotic limb should not exceed 1.5 times the size of the user's upper limb.

5.2 The number factor of robotic limb

The number of the robotic limb also can related to the evaluation indexes, because the SRLs have more functionality with dual robotic limbs than the single robotic limb. This paper analyzed the performance of SRLs with dual robotic limbs, and the robotic limbs have the same size and configuration as the human limb (like Fig. 6).

The Fig. 10 shows the workspace extensiveness calculation for different positions. Compare to Fig. 7, the SRLs can improve the balance between the workspace extensiveness and cooperativeness via robotic limbs secure on the different positions.

For example, the SRLs have low workspace extensiveness when secure on the LSS, and SRLs can increase the extensiveness via another robotic limb secure on the position which has high performance such as the LWS or ABD. And the SRLs with dual robotic limbs have higher workspace cooperativeness than the single one. However, the dual robotic limbs have interfered with each other, so it will cause low workspace safety.

Fig. 10 The performance of evaluation indexes of the different positions with dual robotic limbs

Analyzed the layout of dual robotic limbs, the layout classified the symmetrical layout and asymmetrical layout. In the symmetrical layout, the LWS-RWS has high workspace extensiveness, the LSS-RSS has high workspace cooperativeness, the LWS-RWS has high workspace safety. In the asymmetrical layout, the HDT-ABD has

high workspace extensiveness, the LSA-LWS has high workspace cooperativeness, the LWS-ABD has high workspace safety. The ideal SRLs has a high performance of the evaluation indexes, so the optimal layout is the HDT-ABD by comprehensive evaluation indexes. However, the symmetrical layout is conducive to the gravity balance of the system, therefore the symmetrical layout is more popular in practical application scenarios. This paper thus proposes the two optimal layouts in the asymmetrical layout and symmetrical layout respectively as shown in Fig. 11.

Fig. 11 The high performance of layout with dual robotic limbs

6 Conclusion

This paper presents the evaluation indexes for attachment selection. The range and distribution of the workspace of a wearable robot arm can be quantified and visualized by applying the calculation conditions to the evaluation indexes. The method can predict the human-robot workspace for cooperation, extensive, and safety. An analytical study was conducted in this paper, evaluating indexes based on the evaluation indexes, exploring

5 different positions of the SRLs. From this analysis, the best 2 configurations were identified and simulated. Simulation results demonstrated that the position LSS and ABD performed highly cooperativeness and extensiveness respectively. The evaluation indexes also have potential applications in the design stage, and this paper discusses the two design factors that improve the performance of indexes. one is the length of the robotic limb, the long SRLs may have highly cooperativeness and extensiveness workspace, but also reduce the safety. another is the number of the robotic limb, the SRLs with dual robotic limb can improve the performance of indexes.

In this work, the mass property of the system and the DOF configuration of robotic limbs were not taken into consideration during the simulation analysis. Future works will investigate more this problem, considering also the dynamical characteristics of the robotic limbs. In addition, future works will focus on the design of the SRLs' prototype based on the evaluation indexes, and conduct the validation experiment.

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