平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

書籍

著者氏名	論文タイトル名	書籍全体の編集者名	書籍名	出版社名	出版地	出版年	ページ
山海嘉之	LAB.4　身体機能を拡張するロボットスーツで人の役に立つ	PHP研究所	大人のための「ロボット学」	PHP研究所	東京	2006	93-114
山海嘉之	介護ロボットスーツHAL		地域リハビリテーション	三輪書店	東京	2007	679-684
居村茂幸	第12章リスク管理	吉尾雅春	標準理学療法学＜専門分野＞運動療法学各論第2版	医学書院		2006	400-407
居村茂幸		内山靖	理学療法学事典	医学書院		2006	
居村茂幸		居村茂幸	系統理学療法学 筋骨格障害系理学療法学	医歯薬出版		2006	
居村茂幸	内部障害と理学療法アプローチ	居村茂幸	系統理学療法学 内部障害系理学療法学	医歯薬出版		2006	1-4
居村茂幸	呼吸機能の障害と理学療法	居村茂幸	系統理学療法学 内部障害系理学療法学	医歯薬出版		2007	276-283
中島孝	神経難病のQOL評価から緩和ケアについて	阿部康二	神経内科のすべて	新興医学社	東京	2007	276-283
	ロボットスーツHAL		ニュートンムック 明日を一新する「値千金」の技術32	ニュートンプレス出版	東京	2006	150-151
	コラムNo.03 装着型ロボット（筑波大学開発のロボットスーツHAL）		平成18年版科学技術白書	文部科学省	東京	2006	26
	腕力・筋力が数倍アップする？　夢のロボットスーツ実用化へ		ダカーポ587号	マガジンハウス	東京	2006	41
	「人のパワーをアップしてくれる！」		チャレンジ４年生わくわく発見ブック	ベネッセコーポレーション	東京	2006	7
	"解体"され始めたロボット		知恵蔵2007	朝日新聞社	東京	2006	686

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書籍

著者氏名	論文タイトル名	書籍全体の編集者名	書籍名	出版社名	出版地	出版年	ページ
	ロボットスーツ開発にわくわく		朝日中学生ウィークリー	朝日新聞社	東京	2006	1
	サイボーグ患者宣言		現代思想	青土社	東京	2007	48-67
	この人に聞く！		最新図説政経	浜島書店	東京	2008	293
	パワーをくれるロボットスーツ		テーマ別資料政治経済2008	東京法令出版株式会社		2008	139
			フィロソフィア・ロボティカ-人間に近づくロボットに近づく人間-	毎日コミュニケーションズ	東京	2007	183
	鉄腕アトムが夢でも、サイボーグ009は社会を救える対談　山海嘉之×茂木健一郎		中央公論	中央公論社	東京	2007	124-131
		廣瀬通孝	ヒトと機械のあいだヒト化する機械と機械化するヒト	岩波書店	東京	2007	68
岡野義昭	筑波大学のパワースーツHAL	日高義樹・武藤容治	パブリックセキュリティ　社会の安全と市民の安心を求めて	河出書房新社	東京	2007	272

平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
H. Toda, Y. Sankai	Three-dimensional link dynamics simulator based on N-single-particle movement	Advanced Robotics	19(9)	977-993	2005
H. Kawamoto, Y. Sankai	Power assist method based on phase sequence and muscle force condition for HAL	Advanced Robotics	19(7)	717-734	2005
R. Kosaka, Y. Sankai, R. Takiya, T. Yamane T. Tsutsui	Estimation of Physiologic Strategy based on MathematicalModel for assisting and substituting Cardiac Functions for RoboticArtificial Heart	Advanced Robotics	19(7)	735-750	2005
S. Lee, Y. Sankai	Virtual Impedance Adjustment inUnconstrained Motion for Exoskeletal Robot Assisting Lower Limb	Advanced Robotics	19(7)	773-795	2005
李秀雄, 山海嘉之	装着型下肢用パワーアシストシステムによる振り運動での仮想インピーダンス調整に関する研究	日本機械学会誌C編	71(705)	1686-1695	2005
Hayashi T., Kawamoto H., Sankai Y.	Control Method of Robot Suit HAL working as Operator's Muscle using Biological and Dynamical Information	Proc. of IEEE/RSJ International Conference on Inteligent Robots and Systems (IROS 2005)		3455-3460	2005
Kim Seong Hoon, Sankai Yoshiyuki	Task Generation for Humanoid Robot Walking using Human Motion by Phase Sequence	Proc. of 13th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN 2005)		524-530	2005
Kim Seong Hoon, Sankai Yoshiyuki	Stair Climbing Task of Humanoid Robot by Phase Composition and Phase Sequence	Proc. of 13th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN 2005)		521-536	2005

平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
Suzuki K., Kawamura Y., Hayashi T., SakuraiT., Hasegawa Y., Sankai Y.	Intention-Based Walking Support for Paraplegia Patient	Proc. of Int'l Conf. on Systems, Man and Cybernetics (SMC2005)		2707-2713	2005
H.Toda, T. Kobayakawa, Y. Sankai	A multi-link system control strategy based on biological reaching movement	Advanced Robotics	20(6)	661-679	2006
河本浩明, 塚原淳, 山海嘉之	人間の動作特性を考慮したロボットスーツＨＡＬによる立ち上がり動作支援に関する研究	第7回計測自動制御学会システムインテグレーション部門学術講演会(SI2006)		345-346	2006
Kenta Suzuki, Gouji Mito, Hiroaki Kawamoto, Yasuhisa Hasegawa, Yoshiyuki Sankai	Intention-Based Walking Support for Paraplegia Patients with Robot Suit HAL	Advanced Robotics	21(12)	1441-1469	2007
間瀬教史, 居村茂幸, 北川薫	下肢の骨関節疾患患者の筋力回復と筋線維伝導速度との関係	理学療法学	33 (Suppl.2)	293	2006
Kyoshi Masae, Hiromitsu Kamimura, Shegeyuki Imura, Kaoru Kitagawa	Effect of Age and Gender on Muscle Function –Analysis by Muscle Fiber Conduction Velocity	J. Phys. Ther. Sci.	18	81-87	2006
大瀬寛高、上野友之，河野豊，今泉伸一，西須直美，宮内和喜，阪井康友，居村茂幸，山口直人，永田博司，小國英一	筋萎縮性側索硬化症の呼吸機能評価	日本呼吸ケア・リハビリテーション学会誌	17（1）	76-78	2007
大瀬寛高，阪井康友，居村茂幸，冨田和秀，西須直美，今泉伸一，宮内和喜，齋藤武文	末梢気道病変の検出に対するV25，V50/V25の有用性	日本呼吸ケア・リハビリテーション学会誌	17（1）	41-44	2007
Sankai Y,, Tomita K,, Imura S,, Monma M., Ohse H.	SAGITTAL PLANIMETRY OF THE LUNG IN NORMAL SUBJECTS DURING SPONTANEOUS AND DEEP BREATHING WHILE PRONE: MEASUREMENT USING MRI.	15th International Congress of the World Confederation for Physical Therapy			2007

平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
中島孝	神経難病における遺伝子検査とインフォームドコンセント	神経治療学			2005
中島孝	難病ケアと問題点－QOLの向上とは	臨床神経学			2005
中島孝	ALSのQOL向上と緩和ケア	医療			2005
Atsushi Miki, Takashi Nakajima, Mineo Takagi, Tomoaki Usui, Haruki Abe, Chia-Shang J. Liu, BA, and Grant T. Liu, MD	Near-infrared Spectroscopy of the Visual Cortex in Unilateral Optic neuritis	Am J Ophthalmol	139	353-356	2005
中島孝	難病の生活の質（QOL）研究で学んだこと　―　課題と今後の展望	JALSA	64	51－57	2005
中島孝	生をささえる共通基盤をもとめて－QOLの価値観は健康時から重症時へとどんどん変化していく	難病と在宅ケア	10(12)	7-12	2005
中島孝	QOL評価の新しい挑戦-療養者の物語によるSEIQoL-DWの試み-	日本難病看護学会誌	11巻1号	33-34	2006
伊藤博明、中島孝	在宅神経難病患者のQOL	神経内科	12月号		2006
中島孝	難病のQOL評価と緩和ケア	脳と神経	58(8)	661-669	2006
Nakajima T.	Individual ALS care in the Japanese 'nanbyo'care model: comparison with palliative care approaches in achieving best quality of life	Amyotrophic Lateral Sclerosis	Suppl 1 7	45–47	2006
榛沢和彦，林純一，布施一郎，相澤義房，田辺直仁，中島孝，伊藤正一，鈴木幸雄	新潟県中越大震災被災地住民に対する深部静脈血栓症(DVT)/肺塞栓症(PE)の診断、治療ガイドラインについて	Therapeutic Research	28(6)	1076-1078	2007
中島孝	QOL評価の新しい挑戦　療養者の物語によるSEIQoL-DWの試み	日本難病看護学会誌	11巻３号	181-191	2007
中島孝，川上 英孝，伊藤博明	ALSへのNPPVの導入	Journal of Clinical Rehabilitation	Vol.16No.3	243-250	2007
宮下光令，秋山美紀，落合亮太，萩原章子，中島孝，福原俊一，大生定義	神経内科的疾患患者の在宅介護者に対する「個別化された重みつきQOL尺度」SEIQoL-DWの測定	厚生の指標	55(1)	9-14	2008
中島孝	QOLと緩和ケアの奪還	現代思想	Vol36:2	148-173	2008

平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
中島孝	神経難病と音楽療法　総論	神経内科	67(3)	228-235	2007
中島孝	緩和ケアは看取りの医療ではない-最後まで続くQOLの向上、生きる挑戦	月刊公明	7月号	34-41	2007
	人間の出せない能力をサポートする「モビルスーツ」か	最新科学おもしろ雑学帖	4月号	182	2006
	夢背負うロボットスーツ	読売新聞	4月3日	34	2006
	ロボット着ておんぶ登山	朝日新聞	4月3日	30	2006
	「ロボットスーツ」歩行支援用商品化	朝日新聞	4月11日		2006
	ロボットスーツ　抱っこもひょいっと	朝日新聞	5月24日	38	2006
	ロボットで身体機能拡張	日経産業新聞	6月7日	9	2006
	ロボスーツきょう出発,	信濃毎日新聞	7月31日	26	2006
	Hal-5　l'armure ioniquep	SCIENCE&VIE decouvertes	2006年8月号	18	2006
	ロボットスーツ登山 夢のアルプス挑戦控え「幸せ」	信濃毎日新聞	8月5日	6	2006
	ロボスーツでおんぶ　アルプス４千メートル峰へ	朝日新聞	8月8日	30	2006
	「グッドデザイン」大賞は？	朝日新聞夕刊	10月13日	6	2006
	ロボットスーツ実用化 筑波大学発、介護などに期待	読売新聞	10月29日		2006
	Esqueleto bionico:HAL-5,	Peru21	12月26日		2006
	Shaping our future along with robots	The Japan Times	12月31日	14	2006
	Rise of the body bots	ENGINEERING WORLD		1, 8-13	2007
	ロボットが生活の身近に小型・省エネ・高機能化進む	日本経済新聞	1月1日	元旦第六部, pp. 3	2007
	ロボットスーツ：おかえり HAL-5,	毎日新聞	1月12日	8	2007
	デジタル最前線突撃レポート　ロボットスーツ「HAL」	Saai Isara	2月号	26-29	2007

平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
	ロボット大国日本の新潮流 世界初の歩行を助けるロボットスーツ	nature DIGEST日本語編集版	2月号	18-20	2007
	広がりをみせるデザインの方向性　温かみのある医療機器デザイン	TIME&SPACE	2・3月号	6	2007
	着るロボ家庭に	日本経済新聞	2月15日	3	2007
	「ナイスステップな研究者」科技政策研が10組13人選定	日刊工業新聞	12月27日		2007
	「ナイスな研究者」に13人	毎日新聞	12月27日		2007
	科学技術普及に功績　研究者13人を選出	朝日新聞	12月27日	33	2007
	ナイスステップな研究者：地震速報開発の気象庁・束田氏ら１３人が選ばれる	毎日jp	12月27日		2007
	生体信号を利用したパワースーツ「HAL」は未来をどう変える？	キカイはどこまで人の代わりができるか？職人ロボットから医療ロボットまで～人の暮らしを変えたキカイたち	12月24日	155-158	2007
	サイボーグを思わせるロボットスーツ「HAL」	生命科学の冒険 生殖・クローン・遺伝子・脳	12月4日	170-173	2007
	「正義」こそ日本エンジニアの生きる道 進化の目覚ましい弱者向け技術	日経ビジネスオンライン	１２月３日		2007
	重い荷物もこれでへっちゃら！ロボットスーツHAL	小学三年生	１２月号	16	2007
	次世代へ成熟の街づくり　つくば市制施行20周年	茨城新聞	11月29日	5	2007
	福祉機器展など視察　常陸宮ご夫妻	茨城新聞	11月13日		2007
	ロボットスーツ装着　まなびピア岡山	山陽新聞	１１月５日	23	2007
	ロボット研究と軍事転用　科学者の倫理とは 第3部　「悪用」防ぐ責任	毎日新聞	１１月４日	25	2007
	人間の身体機能をサポートするロボット	碧い風	１１月号	14	2007
	目からウロコの投資塾　産業分析・パートナーロボット編3 レスキュー・介護もお任せ	日本経済新聞夕刊	10月25日		2007

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雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
	～ロボットスーツHAL～　運動機能の客観的評価指標に Medical Tribune	Medical Tribune	10月25日	31	2007
	フロントランナー　筑波大学大学院教授　山海嘉之さん	朝日新聞 be on Saturday	10月13日	26-27	2007
	1．サービス分野における科学的・工学的アプローチの拡大 ④ロボットスーツ	サービス産業におけるイノベーションと生産性向上に向けて（経済産業省編）	10月10日	141	2007
	人の力をパワーアップしてくれる！	チャレンジ４年生わくわく発見ブック	１０月号	7	2007
	身近なロボット、続々開発中！	たしかな目	１０月号	79	2007
	Roboteranzug als Bewegungshilfe fur Gelahmte	EHEALTHCOM	９・１０月号	6	2007
	医療・福祉・生活分野で人と共存する”次世代ロボット”の開発が進んでいる	nature	９月２７日号		2007
	装着すれば誰でもパワーUP！世界初のロボットスーツ	大学受験講座エンカレッジ　物理		52	2007
	着ればあなたもサイボーグ	BCNランキング	９月号	10	2007
	サイボーグ型ロボット「HAL」が人類をパワーアシスト	EVENT REPORT	８月号	130	2007
	「TAMAプロジェクト」「ロボットスーツHAL」が経済産業大臣賞を受賞！	いっとじゅっけん	８月号	26-27	2007
	筑波大学　ロボットスーツHALの開発が「経済産業大臣賞」を受賞	蛍雪時代	８月号	221	2007
	暮らしを変えるロボット大集合	NHK生活ほっとモーニング	７・８月号	55-58	2007
	ロボットを考えることは、人間を考えること	WEBサイト"ロボナブル" 第３回コラムブログ	７月１９日		2007
	「目的達成」へ教授自ら起業	フジサンケイビジネスアイ	７月５日	11版	2007
	The HAL robot suit means the future has super human strength	G'Day Japan	７月号	44	2007
	筑波大ロボット採択　文科省の国際教育支援	日本経済新聞	６月１９日	首都圏経済・茨城35版	2007

平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
	ロボットでリハビリ　筑波大の研究文科省プログラムに選定	朝日新聞	６月１９日	茨城13版	2007
	まさにSFの世界がここに！ロボットスーツHAL	こども写真ひやっか　ロボット大集合	６月１０日	9	2007
	量産ロボットスーツが救う少子高齢化ニッポン	読売ウィークリー	５月２０日	68-69	2007
	HAL Professor Sankai, University of Tsukuba/CYBERDYNE Inc.	jstyle	冬号	30-31	2007
	ロボットスーツで夢実現	朝日新聞	５月１７日	経済12面	2007
	ELET GEEFT STEUN	De Ingenieur	５月４日号	24-25	2007
	Wear a Robot?	WHAT'S UP? 2007-2008 Elementary	５月１日	22-23	2007
	高齢社会の住まい追求	日刊工業新聞	４月１１日	建設・物流13面	2007
	インタビュー　テクノロジーだけで終わらず、育てて守っていく必要がある	日本物流新聞	４月１０日	2面	2007
	いま、この学科が熱い！　筑波大学大学院システム情報工学研究科　ロボットスーツ「HAL」実用化へ	2008年版『学びたい分野』で選べる 大学文系理系学科案内	４月	2	2007
	パワー支援スーツ	発明	４月号	40	2007
	身にまとうロボットスーツ「HAL」が、未来への扉を開く	ケミ・ぱる別冊	４月号	1	2007
	Ungeahnte Krafte dank HAL	Demenz	４月号	30	2007
	夢～未来医療の姿・健康社会の創造～　つくる	第27回日本医学会総会「いのち・ひと・夢 EXPO2007」企画展示 公式ガイドブック	３月３１日発行	35	2007
	"Kleider" machen Leute	JAPAN MARKT	３月号	38	2007
	「人間を守る」使命を	AERA	３月17日号	42	2008
	ロボットスーツHAL	ぷれさん創刊準備号	３月号	6-9	2008

平成１７年度～平成１９年度　研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻名	ページ	出版年
	サイボーグ患者宣言　山海嘉之+松原洋子	現代思想	３月号	48-67	2008
	2008年ロボット新時代	シティオペラ	1月1日-1月20日号	2-3	2008
	「ナイスな研究者」選定	読売新聞	１月６日	19	2008
	障害者も自力歩行	読売新聞	１月４日	33	2008

III. 研究成果の刊行物・別刷り

Advanced Robotics, Vol. 19, No. 7, pp. 717–734 (2005)

Also available online - www.vsppub.com

Full paper

Power assist method based on Phase Sequence and muscle force condition for HAL

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Abstract—An exoskeleton robot can replace the wearer's motion function by operating the human's body. The purpose of this study is to propose a power assist method of walking, standing up and going up stairs based on autonomous motion of the exoskeleton robot suit, HAL (Hybrid assistive Limb), and verify the effectiveness of this method by experiment. In order to realize power assist of tasks (walking, standing up and going up stairs) autonomically, we used the Phase Sequence control which generates a task by transiting some simple basic motions called Phases. A task was divided into some Phases on the basis of the task performed by a normal person. The joint moving modes were categorized into active, passive and free modes according to the characteristic of the muscle force conditions. The autonomous motions which HAL generates in each Phase were designed corresponding to one of the categorized modes. The power assist experiments were performed by using the autonomous motion with a focus on the active mode. The experimental results showed that the wearer's muscle activation levels in each Phase were significantly reduced. With this, we confirmed the effectiveness of the proposed assist method.

Keywords: HAL; exoskeleton; power assist; phase sequence; myoelectricity signal.

1. INTRODUCTION

Exoskeleton robots have been studied in order to amplify human muscle strength. An exoskeleton consists of an external structure which covers the human body parts and has joint parts corresponding to those of the human body. Physical contact between the operator and the exoskeleton causes the integration of the operator and the exoskeleton. The exoskeleton directly provides mechanical power for the operator. Recently, exoskeletons for the human arms and their control methods have

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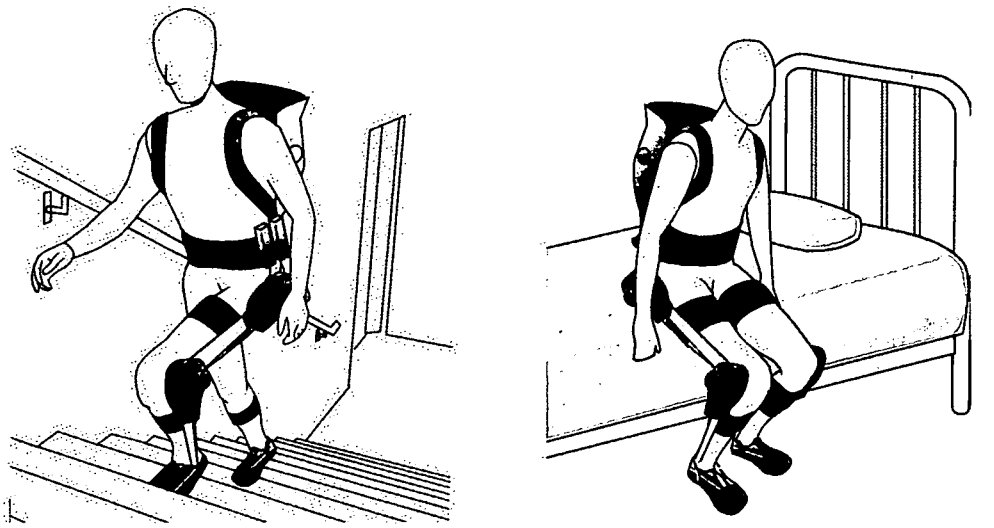


Figure 1. Images of power assist in daily movements.

been studied in order to extend human arm strength in order to reduce the burden imposed on the operator by an external load [1–4]. For example, if an operator wearing the exoskeleton manipulates an external load, the operator may feel 10% of the load while the exoskeleton carries 90% of the load. We have developed the exoskeleton robot suit HAL (Hybrid Assistive Limb) for the lower limb to provide power necessary to perform tasks such as walking, standing up, etc., as shown in Fig. 1. For example, if an operator cannot stand up because he generates only 70% of the muscle strength necessary for standing up by himself, he can stand up while the exoskeleton carries 30% of the muscle strength. We have proposed a power assist method using the joint torque, estimated based on the myoelectric signals that reflect the operator's intention [5–8]. Therefore, a common feature is that the operator manipulates the exoskeleton robot.

An autonomous motion generated by an exoskeleton robot moves the human's body directly. The human becomes a part of the exoskeleton system and the exoskeleton robot operates the human's body. The exoskeleton robot can take the place of the wearer's body function by performing human-like motion autonomically. If the exoskeleton robot has realized tasks such as walking, standing up, etc., the exoskeleton could be used as a functional aid apparatus for gait disorders in persons with spinal cord injury. Our research goal is to develop an autonomous method of motion of the exoskeleton robot in order to aid human leg motion.

When utilizing the exoskeleton robot as a human motion assist apparatus, the exoskeleton should provide motions like those of a human. We have developed the Phase Sequence method, using human motion characteristics, that enable humanoid robots to generate human-like motions [9, 10]. Phase Sequence is a method to generate tasks such as walking, standing up, etc., by transferring some prepared motion elements called Phases. A task is analyzed based on kinematic and

biological information, and divided into a number of Phases according to specific motion intentions like 'swing the leg' or 'lift the body'. For each task, a sequence of Phases is transformed into the motion for the humanoid robot. As a result, the humanoid robot performs the task motions like a human. We attempted to adopt the Phase Sequence method to control the autonomous motions of the exoskeleton robot.

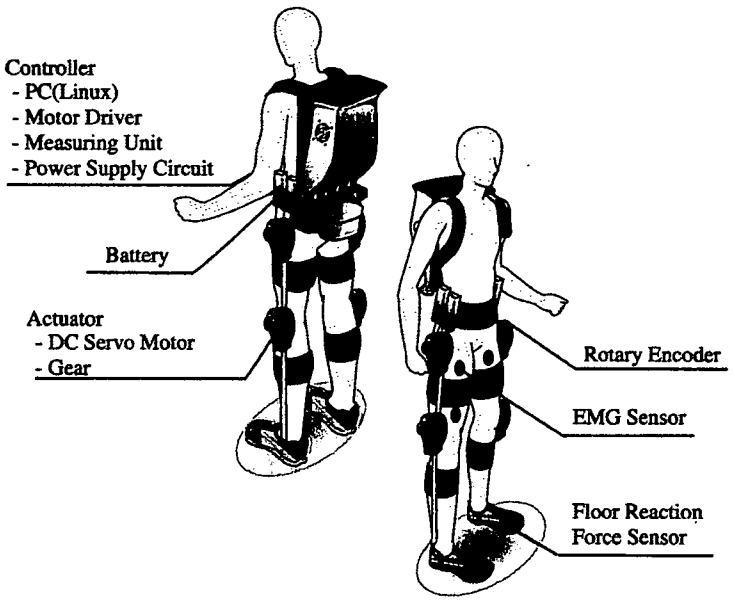
As the wearer and exoskeleton robot are combined into one integrated system, we consider that the motion properties generated by the exoskeleton robot accord to those performed by the wearer. The human realizes tasks using a variety of joint motions based on some modes of muscle activity. Thus, we consider that the exoskeleton robot should be used to generate motions corresponding to joint motions based on modes of muscle activity which a normal person performs. In this study, we propose the Phase Sequence method based on the modes of muscle activity for autonomous motion of the exoskeleton robot HAL. We divide the tasks of walking, standing up and going up stairs into Phases according to joint motion characteristics based on muscle activity. We realize the power assist for these tasks by performing and transforming Phases using HAL.

In Section 2, the details of the exoskeleton robot HAL-3 are described. In Section 3, the tasks of walking, standing up and going up stairs are divided into Phases, and Phase-shift timing for each task is determined. We construct the Phase Sequence control algorithm to generate assist motions. In Section 4, we describe the experiments on motion assists with Phase Sequence control and verify the effectiveness of this method. We give a brief conclusion in Section 5.

2. THE HAL SYSTEM

The HAL-3 system is composed of three main parts: a skeleton with an actuator, a controller and a sensor (Fig. 2).

The exoskeletal frame consists of a three-link, two-joint mechanism with the links corresponding to the hip, the thigh and the lower thigh, and the joints corresponding to the hip and the knee joints of the human body. Aluminum alloy and steel are used for the exoskeletal frame in consideration of lightness. The knee joint of the exoskeleton has 1 d.o.f. The human hip joint complex can be considered as a 3-d.o.f. joint. The exoskeleton, in its current mode, supports only the flexion–extension movement of the hip joint. The ankle joint has also 1 d.o.f., i.e. dorsiflexion–planterflexion. As shown in Fig. 3, the rigid sole is fitted with a fastener that is connected to the end of the lower thigh exoskeletal frame, which is provided with a swivel attachment. This swivel attachment corresponds to the ankle joint with 1 d.o.f. The joint limiters are equipped at the respective joints to prevent hyperextension of the hip and the knee joints. This exoskeleton system attaches to the hip, thigh, lower thigh and foot area of the body. At these areas (except the foot area), belts which are designed as shell garments of these areas worn by the wearer, are located at each link. At the foot area, the soles of the exoskeleton in which the wearer rides are provided. Since the human lower limb and the exoskeleton



(a)

(b)

Figure 2. The HAL-3 system. (a) Schematic overview. (b) System overview.

are mechanically linked, the movements of both legs of both the human and the exoskeleton are identical. The actuators of HAL-3 provide assist torque for the knee and hip joints. Each actuator has a DC motor with a harmonic drive to generate the assist torques at each joint. The ankle joints are not powered by a motor. If human walks quickly, the kick produced by the toe is used. We do not assume the

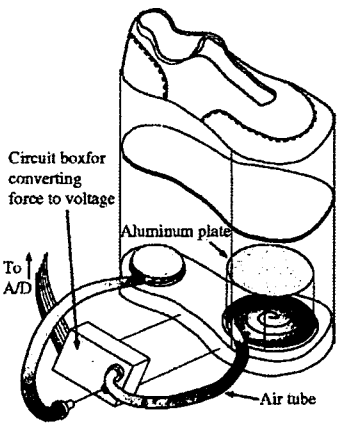


Figure 3. FRF sensor system.

assist for walking speed using the kick. We consider that the ankle joints play a important role in maintaining stability in the support phase. The spring mechanism is incorporated in the ankle joint of HAL-3. The total weight of the skeleton system with the actuators is about 15 kg. The wearer does not have to bear the weight load of the exoskeleton by riding on the soles of the exoskeleton, because the weight of the exoskeleton is transmitted to the floor, bypassing the soles.

Sensor systems are equipped on HAL-3 to detect the conditions of HAL and the wearer. Rotary encoders are used to measure the hip and knee joint angles. A floor reaction force (FRF) sensor is developed to measure the FRFs which are generated in the front and rear parts of the foot (ball and heel of foot). This sensor structure is shown in Fig. 3. It consists of a sole and electronic circuits parts. In the sole of the shoe, two coiled polyvinyl chloride tubes (inner diameter 3 mm) sandwiched by circular aluminum boards are installed. One end of the tube is connected to a solid-state pressure sensor attached on the electronic circuit. When the foot presses the tube, the air pressure in the tube changes. The change of air pressure is measured by the pressure sensor. With this, we can detect the FRF from the change of the air pressure. Myoelectric sensors are attached on the surface of the extensor and the flexor of the knee and the hip to detect muscle activity. Each myoelectric sensor consists of a bipolar electrode and a pre-amp, which reduce noise substantially. The myoelectric signals are first measured through the bipolar skin surface electrodes attached to the skin on top of the muscle and amplified by 106 times, and then filtered using a low-pass filter (with a cut-off frequency at 500 Hz) and a high-pass filter (with a cut-off frequency at 33 Hz) in the back pack to remove noise caused by motion artifacts.

The control system of HAL-3 is mainly developed to enhance mobility because the field of activity for of HAL-3 assistance is expected to be in outdoor activities. Thus, we designed a compact-type PC which is the controller, the motor drivers, the power supply for the PC and other circuits, EMG signals processing board and sensor interface boards to be packed in the back pack. The PC has a Celeron 566 Hz

CPU, a wireless LAN card (11 Mbps transmission speed), an A/D converter card which has a 32-channel (12-bit resolution) input and a D/A which has an 8-channel (12-bit resolution) output. Real-time processing and network communication are required for the control scheme. To make the development environment convenient, we adopt different operating systems for the measurement process and control process. RT-Linux is used for the measurement process. It is able to measure sensor information in real-time. On the other hand, we use Linux for the control process. Real-time processing can be achieved in practical use by modifying only one parameter of the Linux kernel source file. Thus, the control loop is executed in user mode by using this approach which almost guarantees a fixed control period [11]. To monitor sensor information with the remote controller in real-time, radio communication using UDP is utilized between the HAL controller and the remote controller.

3. POWER ASSIST METHOD

In this section we describe how to a divide series of motion into Phases and how to transit each Phase in order to apply the Phase Sequence method to the power assist system HAL-3.

3.1. Muscle condition

In the various tasks (walking, standing up, etc.), each muscle generates force mainly based on threes mode of muscle force conditions, i.e. active, passive and free, depending on the direction of muscle length contraction and external forces as shown in Fig. 4. In the case of the rectus femoris, the muscle length is shortened as its contractive force is generated in the active mode (Fig. 4a). This is mainly based

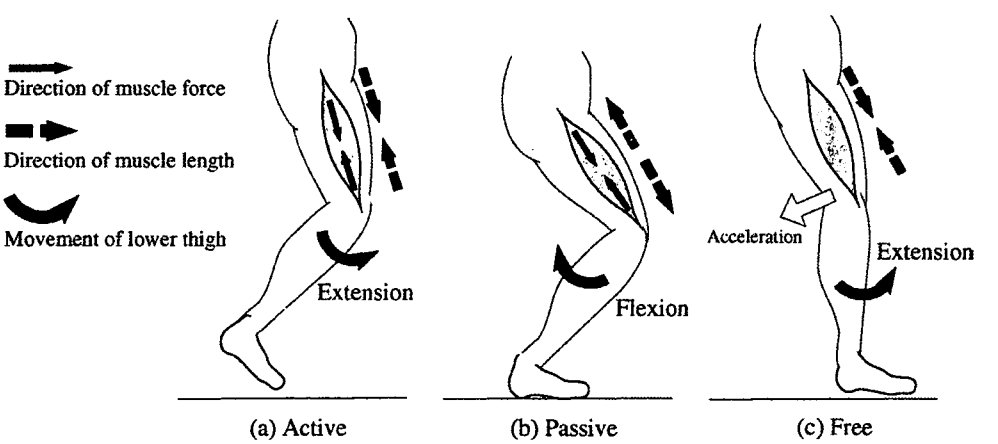


Figure 4. Muscle force mode depending on the relationship between the direction of muscle force and the direction of muscle length contraction.

upon the contractile element. In the passive mode (Fig. 4b), the muscle length is lengthened as its contractive force is generated. These muscles play the role of an viscoelastic element. In the free mode (Fig. 4c), the muscle contractive force is not generated. The movement of the lower thigh is generated by the force caused by knee acceleration or gravity. As the result, the knee joint behaves like a free joint. It should be effective for the power assist to generate assist motions corresponding to the wearer's muscle conditions.

3.2. Phase division

We analyzed the motion of a normal person during each task (walking, standing up and going up stairs) to divide it into some Phases according to the three modes based on muscle activity and direction of muscle length. The joint angle is assumed to be proportional to the muscle length. The muscle activities are estimated from the behavior of myoelectric signals of the flexor and the extensor. The subject was a normal 28-year-old male.

3.2.1. Walking. Figure 5a shows the joint angles and myoelectric signals for the hip and knee joint, and FRFs in the front and rear parts of the sole of the feet while walking. Each joint angle is set as 0 rad in the standing posture. Its positive and negative direction indicate flexion and extension, respectively. A positive sign of the myoelectricity corresponds to the flexor muscles and a negative sign corresponds to the extensor muscles. The activation level of the myoelectricity is represented in the range of ± 5 V. The motion of walking is mainly divided into two phases — the support phase and the swing phase. The swing phase is the behavior where the foot leaves the ground surface and the leg swings forward. The support phase is the behavior where the foot stays in contact with the ground surface and the body is supported by the leg. In the swing phase (Phase 1), when the hip joint is bent, the myoelectric signals at the flexor of the hip are generated. The hip flexor works in active mode. At the same time, the knee joint is bent from the extension position and is extended after that. During the swing period the myoelectric signals at the flexor and the extensor of the knee joint are generated slightly. It is considered that the lower thigh is forced to move by the inertial force generated by the thigh. Therefore, the knee joint works in the free joint mode. In the support phase (Phase 2), when the hip joint is extended, the myoelectric signals at the extensor of the hip are barely generated. The hip extensor works in active mode. The knee joint is slightly bent from the extension position and is extended after that. The myoelectric signals at the extensor of the knee joint are largely generated when the knee joint is bent. The antagonist muscle (the extensor) performs lengthening contraction to absorb the shock to the knee joint from upper body when the foot makes contact with the ground surface. Therefore, the knee joint would work in passive mode.

3.2.2. Standing up. Figure 5b shows the joint angles and myoelectric signals for the right hip and knee joints, and FRFs in the front and rear parts of the right

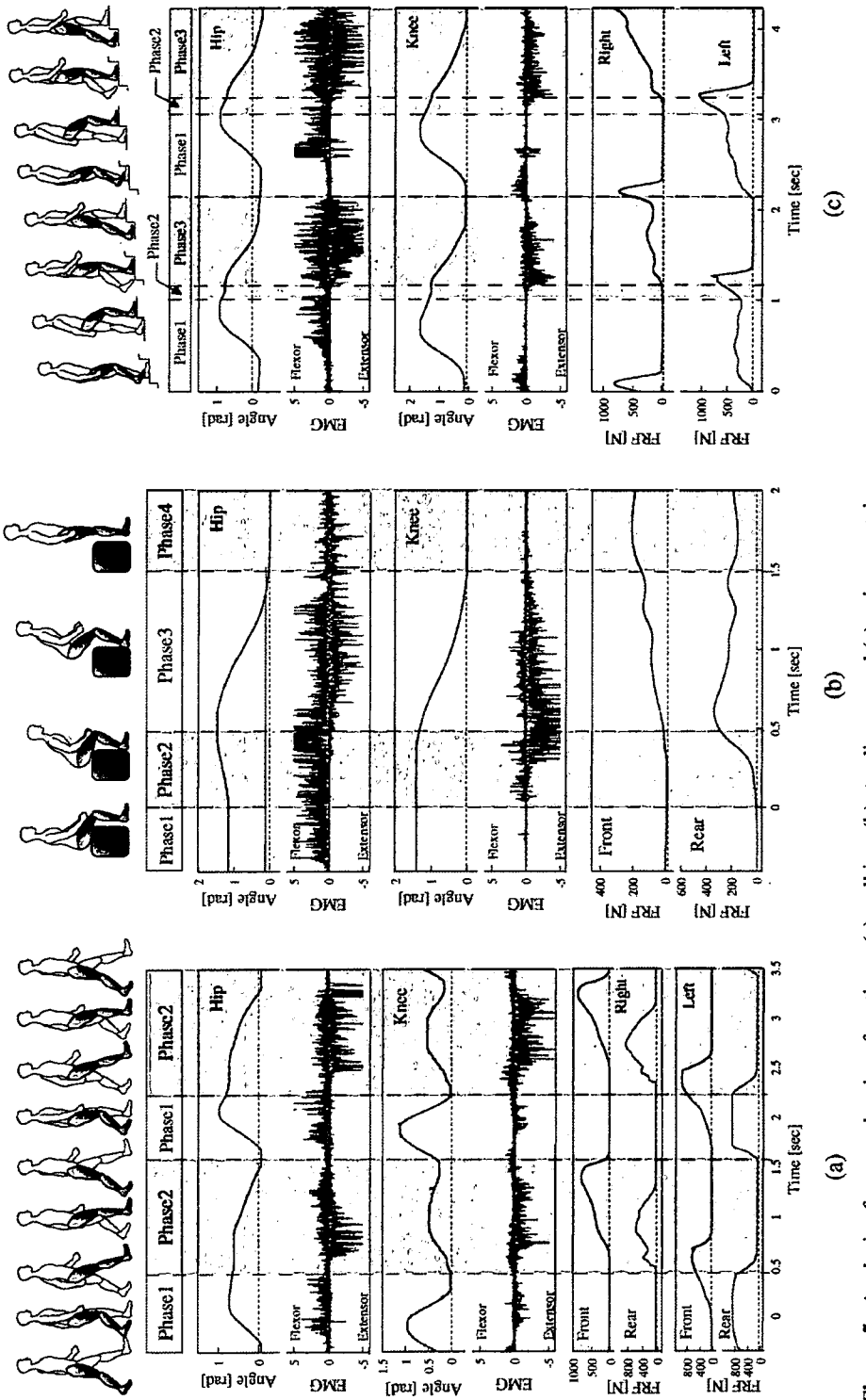


Figure 5. Analysis of a normal series of motions: (a) walking, (b) standing up and (c) going up stairs.

foot while standing up. The subject begins to stand up from the initial condition that the subject sits on a chair which is approximately 40 cm high, and maintains the knee and hip joints at near 1.5 rad. The motion of standing up from a chair is mainly divided into four phases. Phase 1 is the sitting position. Phase 2 is when the upper body is bent forward. Phase 3 is when the upper body is lifted as the angles of the hip joints attained the maximal value. Phase 4 is the standing position. Phases 2 and 3 are especially important to assist standing up. We analyze the muscle condition from myoelectric signals on Phases 2 and 3. In Phase 2, myoelectric signals are generated by the flexor of the hip and the extensor of the knee; when the hip joint is flexed, the knee joint is slightly extended. In Phase 3, when the hip and knee joints are extended, myoelectric signals are generated by the extensors of both joints. Because each muscle performs shortening contraction in Phases 2 and 3, both joints work in the active mode in each Phase.

3.2.3. Going up stairs. Figure 5c shows the joint angles and myoelectric signals for the right hip and knee joints, and FRFs in the front part of the both feet while going up stairs. The subject goes up stairs that are 15 cm high and 30 cm wide. The motion of going up stairs is mainly divided into three Phases. Phase 1 is the behavior that the foot lifts from the stair surface and the leg is lifted up. Phase 2 is the behavior that the leg is slightly lowered in order to establish contact of the foot with the stair surface, after the foot is lifted up above the stair surface in Phase 1. Phase 3 is the behavior that the foot contacts with the stair surface and the body is lifted up. In Phase 1, when the hip joint is bent, the myoelectric signals at the flexor of the hip are generated. Thus, the hip flexor works in active mode. On the other hand, when the knee joint is bent, the myoelectric signals at the flexor and the extensor of the knee joint are generated slightly. The knee joint is bent by lifting the thigh without moving the lower thigh. The flexor and the extensor of the knee joint do not act. Therefore, the knee joint works in the free joint mode. In Phase 2, when the hip and knee joints are extended slightly, the myoelectric signals at the flexor and the extensor of both joints are generated slightly. Each joint works in free mode. In Phase 3, when the hip and knee joints are extended, the myoelectric signals at the extensor of the hip and knee are generated. Each extensor works in the active mode. As explained above, we divide the tasks (walking, standing up and going up stairs) into Phases. Figure 6 shows the joint part, direction and dynamic mode in each Phase for walking, standing up and going up stairs.

3.3. Phase-shift timing

To realize power assist by using Phase Sequence, the prepared Phases have to smoothly transit. The Phase-shift timing needs to reflect the wearer's intention. If the Phase generated by HAL does not accord to the Phase which the wearer intends, HAL may provide unnecessary load to the wearer and the wearer would feel uncomfortable. In this section, we determine Phase-shift timing on the basis of the motion of a normal person. Most motions of the lower limbs of a person