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REVIEW

Evaluation Methods for the Assist Suit and Agricultural Applications

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Abstract

Labor-saving technology has seen developments as the farmer population ages in Japan, and one of them is the assist suit. The assist suit can be categorized into exoskeleton and supporter types based on whether it is rigid and into active and passive types based on whether it is powered. The evaluation methods of the assist suit can be broadly classified into biomechanical analysis, physiological evaluation, and psychological evaluation. JIS B 8456-1 provides a method for measuring the mechanical assistive force, which is a static force or torque, of the lumbar support type, and we developed a method for measuring the dynamic assistive force, which is a dynamic force or torque, as a method building on top of the JIS method. The assistive forces can be compared with the tolerance of the human joints to estimate the operational safety of the assist suit on a human. Lifting and transporting objects, holding a half-sit posture, and picking fruits are representative tasks expected to utilize the assist suit in agriculture. In Japan, falls are considered the most important hazard because farmers often work on uneven ground with poor footing surrounded by many obstacles.

Discipline: Agricultural Engineering
Additional key words: exoskeleton, farm work, torque, wearable robot

Introduction

The global population is aging, and the percentage of the population aged 65 years or over is expected to rise to 16% by 2050, which means one in six people will be 65 years or older globally. Population aging is fastest in Eastern and South-Eastern Asia, with the largest number of older populations aged 65 or above, which is 261 million in 2019, growing to 573 million in 2050. Japan has the most aged population and the highest old-age dependency ratio in the world at 51%, which is projected to be 81% in 2050 (United Nations 2019). The aging of the farmer population is particularly serious among all industries in Japan. The percentage of farmers aged 65 years or over who make their living primarily from agriculture has risen yearly to 70% in 2022. Furthermore, new farmers coming into agriculture every year have also aged; two in three new farmers were over 50 years old in 2021 (MAFF 2022). The agricultural workforce in Japan is strongly dependent on aged farmers, and this trend will continue.

Labor-saving technology can allow these farmers to sustainably work healthily throughout their lives to maintain agricultural production, and smart agriculture has been attracting attention in Japan in recent years. Smart agriculture is agriculture that utilizes advanced technologies such as robots, AI, and IoT, such as autonomous tractors, combine harvesters, rice transplanters, etc. One such technology is the assist suit. The assist suit is a wearable suit that can assist with body movement and posture to reduce the physical load and can provide support for manual handling in farmwork because there are still manual tasks that are not replaced by machines and robots, especially in mountainous

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regions where smallholder farmers live in Japan. Furthermore, even in situations where these machines and robots are utilized, there can be manual handling between the tasks they perform, such as supplying fertilizers and seedlings to the machines and robots.

Various types of assist suits have been developed in Japan for various applications, such as manufacturing, construction, logistics, nursing care, and agriculture. In addition, there are already many products on the market today. Therefore, the market has demanded methods to evaluate these assist suits properly.

In this review, we will introduce the types of assist suits and evaluation methods and describe our works, including evaluation methods and risk assessment of assist suits for agricultural utilization.

What is assist suit

The term "assist suit" has not been defined clearly but is generally considered in Japan as something wearable that assists human movement and posture. Such devices are called various names around the world, such as the power assist suit, assisted suit, powered suit, powered exoskeleton, exoskeleton suit, exosuit, etc. Here, we call all these technologies the assist suit. The assist suit can be classified into four categories, depending on whether its structure is rigid and whether it has a power source. The exoskeleton type comprises several rigid materials, and their actuators are also rigid. The supporter type comprises elastic fabrics and rubbers without a rigid body and actuator. The active type has an internal or externally supplied power source driving electric, pneumatic, hydraulic power, or the like. The passive type has no power source but can passively support its structure or release the force accumulated inside from human motion and posture. We classified products for industrial and consumer utilization in the global market in Table 1.

Assist suits are worn over part or the entire human body and assist with some or all the forces normally exerted by human joints. However, as demonstrated in Figure 1, even with an assist suit that works on the same joint, the intended physical task and body part differ depending on the direction of the assisting force. We have categorized the product groups in Table 1 according to which human joint axis the assist suit functions on and further which body part it assists. There are many products, especially for lumbar or upper limb assistance on the hip or shoulder joint, often with the optional functions of covering other joints throughout all types in Table 1. Lumbar support is the most popular utilization of exoskeleton-active type products. Exoskeleton-passive type products are the most out of all products, particularly the variety of products that assist the lumbar or arm, forearm, and upper limb stand out. The active type has the fewest products; the supporter-passive type is the second most common product after the exoskeleton-passive type, and lumbar support is the most popular application.

Evaluation methods of the assist suit globally

The proposed assessment methods are summarized in Table 2. Exoskeleton evaluation variables vary with the selection of evaluation criteria. In biomechanical evaluation, the physical loads acting on the lumbar can be utilized to evaluate the safety or effectiveness of the exoskeleton. The reduction of peak lumbar compressive force, lumbar shear force, and lumbar torque indicate how much one exoskeleton can reduce lumbar burden (Marras et al. 2000, Weston et al. 2018, Koopman et al. 2019b, Abdoli et al. 2007, Ito et al. 2018, Nabeshima et al. 2018, Koopman et al. 2019a). Physiological evaluation focuses on energy expenditure, which often manifests as lumbar fatigue after sustained repetitive actions. Elevated fatigue levels correspond with a reduction of electromyography median frequency (MNF) (Godwin et al. 2009, Xiong et al. 2019, Dos Anjos et al. 2022) and peak normalized EMG (Ulrey et al. 2013, Lamers et al. 2017, Huysamen et al. 2018, Koopman et al. 2019a) but an increase of the root mean square (RMS) (Godwin et al. 2009, Tan et al. 2019, Dos Anjos et al. 2022) of electromyography (EMG), heart rate (Godwin et al. 2009), and oxygen consumption (Whitfield et al. 2014). Utilizing an exoskeleton is expected to reduce lumbar fatigue and, therefore, reduce the absolute value of the tendency slope of the physiological factors in time history. Psychological evaluations typically are carried out by scoring how hard physical activity is or how fatigued you feel during physical activity according to a certain scale such as subjective surveys (Abdoli et al. 2008), perceived exertion ratings (Godwin et al. 2009, Huysamen et al. 2018), and the visual–analog scale (VAS) (Baltrusch et al. 2019). Kinematics evaluations of exoskeletons usually focus on the restriction of the maximum joint angle, velocity, and acceleration (Marras et al. 2000, Abdoli et al. 2007, Ulrey et al. 2013, Lamers et al. 2017, Koopman et al. 2019a, Koopman et al. 2019b, Whitfield et al. 2014, Tan et al. 2019, Sadler et al. 2011). In functionality evaluation, given the diverse nature of tasks and their inherent compound actions, it becomes necessary to evaluate other factors such as task duration, precision, and qualitative outcomes (Lamers et al. 2017, Baltrusch et al. 2019).

Table 1. Products related to assist suit globally and classification

How to view the Products classification table[a]

		Structure	
		Exoskeleton type[b]	**Supporter type[c]**
Power source	**Active type[d]**	**Human joints[f]** **Human body parts[g]** Product name (Company Name_Country name)	
	Passive type[e]		

[a] Only industrial and consumer products, excluding army, medical, rehabilitation, etc., were extracted on the Internet from June 2023 to May 2024.
[b] Exoskeleton type means assist suit with rigid body and actuator.
[c] Supporter type means assist suit without rigid body and actuator.
[d] Active type means assist suit with power source driven by electric, pneumatic, hydraulic, etc.
[e] Passive type means assist suit without a power source.
[f] Products were classified by which human joint they worked on or replaced.
[g] Products were classified by the intended body part they assist with.

Products classification table

		Structure	
		Exoskeleton type	**Supporter type**
Power source	**Active type**	**Hip joint** **Lumbar Support** NON-MEDICAL HAL LUMBAR TYPE FOR WELL-BEING (CYBERDYNE_Japan) PAIS-M100 (POWER ASSIST INTERNATIONAL_Japan) PAIS-A100 (POWER ASSIST INTERNATIONAL_Japan) SUPPORT JACKET Ep+ROBO (upr_Japan) Exoback (RB3D_France) Apogee (German Bionic_Germany) Apogee+ (German Bionic_Germany) Cray X (German Bionic_Germany) Active Trunk module (Robo-Mate_Schweiz) **Thigh Support** Physibo Walk GH-3000 (OG Wellness_Japan) Hector H30A (HEXAR_Korea) **Shoulder joint** **Arm Support** ARM-1D (Kubota_Japan) AGADEXO SHOULDER (AGADE_Italy) **Upper limbs Support** ENFORCER (ExoMed_Russia) **Elbow joint** **Forearm Support** EduExo 2.0 (Auxivo_Switzerland) **Hip and Shoulder joint** **Lumbar and Upper limbs Support** Muscle Upper (Innophys_Japan) WIN-1(Kubota_Japan)	**Hip joint** **Lumbar Support** Assist Vest (ALPHA TECHNICAL RESEARCH_Japan) J-PAS Agri~ (J-TEKT_Japan) J-PAS fleairy (J-TEKT_Japan) **Hand joint** **Finger Support** DARWING Power Assist Glove (DAIYA_Japan) Ironhand (BIOSERVO_Sweden)

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Products classification table (Continued 1)

		Structure	
		Exoskeleton type	**Supporter type**
Power source	**Active type**	**Hip and Knee and Ankle joint** **Lower limbs Support** Bodyweight Support Assist (Honda_Japan) **Shoulder and Elbow joint** **Arm and Forearm Support** EduExo Pro (Auxivo_Switzerland) Active Arms module (Robo-Mate_Switzerland)	
Power source	**Passive type**	**Hip joint** **Lumbar Support** Muscle Suit GS-BACK (INNOPHYS_Japan) Muscle Suit Every (INNOPHYS_Japan) Muscle Suit Exo-Power (INNOPHYS_Japan) Way-sist (TOYOFLEX_Japan) UPLIFT Back (MAWASHI_Canada) CDYB-EP (Crimson Dynamics Technology_China) Wave (HMT_France) BionicBack (hTRIUS_Germany) Ottobock BackX (ottobock._Germany) MATE-XB (MATE_Italy) Hector L20P(HEXAR_Korea) ExoAtlant Torso (ExoAtlet_Luxembourg) LAEVO FLEX (Laevo_Netherlands) LAEVO V2 (Laevo_Netherlands) ExoAtlant Torso (EXOATLET_ Russia) EXOWAIST (CYBER HUMAN SYSTEM_Spain) IX BACK (SUITX by ottobock_USA) IX BACK AIR (SUITX by ottobock_USA) **Knee joint** **Thigh Support** Chairless Chair 2.0 (noonee_Germany) Againer (AGAINER_Slovenia) Ski~Mojo (Ski~Mojo_UK) **Shoulder joint** **Arm Support** TASK AR Type S (DAYDO_Japan) TASK AR 2.0 (DAYDO_Japan) Muscle Suit GS-ARM (INNOPHYS_Japan) TasKi (SoLARIS_Japan) Exy ONE (Exy Innovation Company_Brazil) CDYS (Crimson Dynamics Technology_China) EXHAUSS PICKER configuration Delta (EXHAUSS_France) EXHAUSS STRONGER Configuration Reliever (EXHAUSS_France) EXHAUSS SXSTEM RELIEVER (EXHAUSS_France) HAPO UP (Ergosanté SA_France) Plum' (HMT_France) Ottobock Shoulder (ottobock._Germany) MATE-XT (MATE_Italy) MATE-XT 4.0 (MATE_Italy) VEX (Hyundai Motor_Korea) X-RISE (XORISE_Russia) EXOSHOULDER (CYBER HUMAN SYSTEM_Spain) DeltaSuit (AUXIVO_Switzerland) AIRFRAME FLEX (LEVITATE_USA) Ekso EVO (eksoBIONICS_USA) IX SHOULDER (SUITX by ottobock_USA)	**Hip joint** **Lumbar Support** Aero Back (ASAHI RENTAX_Japan) Aero Back SG (ASAHI RENTAX_Japan) Luftvest (ALPHA TECHNICAL RESEECH_Japan) Agri Power Suit (Atelier-k_Japan) Working Power Suit (Atelier-k_Japan) WORKING POWERSUIT X (Atelier-k_Japan) DARWING Hakobelude (DAIYA_Japan) DARWING PA-Jacket (DAIYA_Japan) DARWING SATT (DAIYA_Japan) DARWING SATT + Lower limb option (DAIYA_Japan) DARWING select Venus (DAIYA_Japan) DARWING surgical model (DAIYA_Japan) DARWING Working assist LB (DAIYA_Japan) Shokunin DARWING-Ttype (DAIYA_Japan) Shokunin DARWING Komachi Ttype (DAIYA_Japan) Muscle Suit Soft-Light (INNOPHYS_Japan) Muscle Suit Soft-Power (INNOPHYS_Japan) Raku wear (Kikuchiseisakusho_Japan) CBW (KURABO_Japan) rakunie (MORITA_Japan) Assist gear (NIPPON SIGMAX_Japan) Smart Suit Lite (Smart Support Technologies_Japan) Smart Suit Plus (Smart Support Technologies_Japan) Inner Support Suit (TOGASHI_Japan) Power Mesh Support Suit (TOGASHI_Japan) Work Support Suit (TOGASHI_Japan) SUPPORT JACKET Bb+Air (upr_Japan) SUPPORT JACKET Bb+FIT SLIM (upr_Japan) SUPPORT JACKET Bb+FIT WIDE (upr_Japan) SUPPORT JACKET Bb+PROIII (upr_Japan) HAPO SD (Ergosanté SA_France) Paexo Soft Back (ottobock._Germany) LOWEBACKER (ExoMed_Russia) X-SOFT (XORISE_Russia) X-SOFT Lady (XORISE_Russia) EXOSOFT (CYBER HUMAN SYSTEM_Spain) HELK (GOGOA_Spain) LiftSuit 2 (AUXIVO_Switzerland) The Apex 2 (HEROWEAR_USA) **Knee joint** **Leg Support** Working Power Suit knee supporter (Atelier-k_Japan) **Shoulder joint** **Arm Support** Shokunin DARWING Komachi Xtype (DAIYA_Japan) Shokunin DARWING-Xbtype (DAIYA_Japan) Shokunin DARWING-Xtype (DAIYA_Japan)

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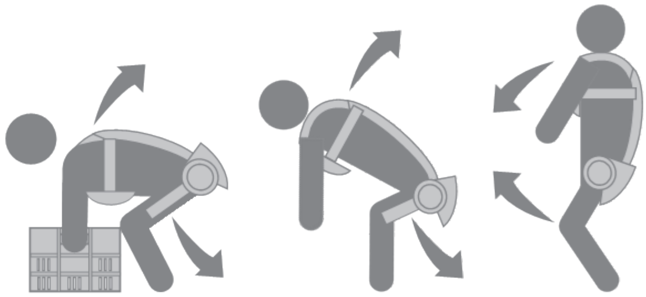
Products classification table (Continued 2)

		Structure	
		Exoskeleton type	**Supporter type**
Power source	**Passive type**	**Elbow joint** **Forearm Support** TASK AR ＋ (DAYDO_Japan)	**Ankle joint** **Leg Support** DARWING calf (DAIYA_Japan)
		Neck joint **Neck Support** MooN (HMT_France) Paexo Neck (ottobock._Germany)	**Hand joint** **Finger Support** Paexo Wrist (ottobock._Germany)
		Hand joint **Finger Support** Paexo Thumb (ottobock._Germany)	**Hip and Knee joint** **Thigh Support** DARWING Arukerude PRO (DAIYA_Japan) **Lumbar and thigh Support** DARWING Arukerude + upper body option (DAIYA _Japan)
		Hip and Knee joint **Lumbar and Thigh Support** UPLIFT Back+Knees (MAWASHI_Canada)	**Hip and Knee and Elbow joint** **Lumbar and Leg and Forearm Support** Working Power Suit Kiwami (Atelier-k_Japan)
		Hip and Shoulder joint **Lumbar and Arm Support** UPLIFT Back+Arms (MAWASHI_Canada)	**Hip and Knee and Ankle and joint** **Thigh and Leg Support** DARWING standard model lower body (DAIYA_Japan)
		Hip and Knee and Shoulder joint **Lumbar and Thigh and Arm Support** UPLIFT All modules (MAWASHI_Canada)	**Hip and Knee and Shoulder and Elbow and Ankle joint** **Lumbar and Thigh and Arm and Forearm and Leg Support** DARWING standard model full body (DAIYA_Japan)
		Knee and Ankle joint **Thigh and Leg and Lumbar Support** archelis (archelis_Japan) archelisFX (archelis_Japan) archelisFXstick (archelis_Japan)	**Hip and Shoulder and Elbow joint** **Lumbar and Arm and Forearm Support** e.z.UP (Asahicho_Japan) EXOARMS (CYBER HUMAN SYSTEM_Spain) DARWING Hakobelude + arm option (DAIYA_Japan) DARWING standard model upper body (DAIYA_Japan)
		Shoulder and Elbow joint **Forearm and Arm Support** EXHAUSS PICKER configuration Ulna (EXHAUSS_France) EXHAUSS STRONGER Configuration Worker (EXHAUSS_France) EXHAUSS SXSTEM ORBITER (EXHAUSS_France) EXHAUSS SXSTEM WORLER (EXHAUSS_France) HOLDUPPER (ExoMed_Russia) Passive Arms module (Robo-Mate_Schweiz)	**Shoulder and Elbow joint** **Arm and Forearm Support** DARWING Agerelude (DAIYA_Japan) DARWING Working assist AS (DAIYA_Japan) HAPO FRONT (Ergosanté SA_France)
		Shoulder and Elbow and Hand joint **Upper limbs Support** ATLAS SYSTEM (EXOMYS_Austria) Armor-Man 2 (TILTA/TILTA MAX_China) EXHAUSS PICKER configuration Meta (EXHAUSS_France) EXHAUSS STRONGER Configuration Lifter (EXHAUSS_France) EXHAUSS STRONGER Configuration Transporter (EXHAUSS_France) EXHAUSS SXSTEM LIFTER (EXHAUSS_France) EXHAUSS SXSTEM TRANSPORTER (EXHAUSS_France) EXHAUSS SXSTEM UPPER (EXHAUSS_France) X-ARM (XORISE_Russia) CarrySuit (AUXIVO_Switzerland)	

The evaluation variables can be directly recorded by biomedical measurement systems or digital simulations. The variables, such as surface EMG, ground reaction force (GRF), movement, contact pressure, heart rate, and oxygen consumption, can be directly obtained via the instrumentations. However, variables such as lumbar



Task	Lifting	Holding	Walking
Body part	Lumbar	Lumbar	Thigh

Fig. 1. Force direction of assist suit acting on the hip joint and intended task and body part

Table 2. Summary of proposed assessment method for exoskeletons

Method	Criterion	Dependent factors	Independent factors	Statistics
Biomechanical analysis	kinematics	**peak trunk angle** (Marras et al. 2000, Abdali et al. 2007, Ulrey et al. 2013, Lamers et al. 2017, Koopman et al. 2019a, Koopman et al. 2019b) **peak trunk angular velocity** (Marras et al. 2000, Koopman et al. 2019b) **peak trunk angular acceleration** (Marras et al. 2000) **peak hip angle** (Abdoli et al. 2007, Ulrey et al. 2013, Whitfield et al. 2014, Koopman et al. 2019a, Tan et al. 2019, Dos Anjos et al. 2022) **mean hip angular velocity** (Tan et al. 2019) **peak knee angle** (Ulrey et al. 2013, Whitfield et al. 2014, Dos Anjos et al. 2022) **peak ankle angle** (Ulrey et al. 2013, Whitfield et al. 2014) **principal component score of joint angles** (Sadler et al. 2011)	**assistance** (Marras et al. 2000, Abdoli et al. 2007, Sadler et al. 2011, Ulrey et al. 2013, Whitfield et al. 2014, Lamers et al. 2017, Koopman et al. 2019a, Koopman et al. 2019b, Tan et al. 2019, Dos Anjos et al. 2022) **asymmetry** (Marras et al. 2000) **weight** (Marras et al. 2000, Abdoli et al. 2007, Ulrey et al. 2013) **height** (Marras et al. 2000, Koopman et al. 2019a) **style of lifting** (Abdoli et al. 2007) **lifting phase** (Tan et al. 2019, Dos Anjos et al. 2022) **left or right sides** (Dos Anjos et al. 2022)	**ANOVA** (Marras et al. 2000, Ulrey et al. 2013, Koopman et al. 2019a, Koopman et al. 2019b, Dos Anjos et al. 2022) **t-test** (Abdoli et al. 2007, Whitfield et al. 2014, Lamers et al. 2017) **Principal component analysis** (Sadler et al. 2011) **Wilcoxon signed rank test** (Koopman et al. 2019a, Tan et al. 2019)
	kinetics	**maximal lumbar moment** (Marras et al. 2000, Koopman et al. 2019a, Koopman et al. 2019b) **peak lumbar shear force** (Marras et al. 2000, Weston et al. 2018, Koopman et al. 2019b) **peak lumbar compressive force** (Marras et al. 2000, Weston et al. 2018, Koopman et al. 2019b) **peak assisted moment** (Abdoli et al. 2007, Ito et al. 2018, Nabeshima et al. 2018, Koopman et al. 2019a) **peak lumbar shear and compressive force reduction** (Abdoli et al. 2007) **peak resultant reaction force** (Abdoli et al. 2007)	**assistance** (Marras et al. 2000, Abdoli et al. 2007, Abdoli et al. 2008, Huysamen et al. 2018, Ito et al. 2018, Nabeshima et al. 2018, Weston et al. 2018, Koopman et al. 2019a, Koopman et al. 2019b) **asymmetry** (Marras et al. 2000, Abdoli et al. 2008, Weston et al. 2018) **weight** (Marras et al. 2000, Abdoli et al. 2007, Abdoli et al. 2008, Huysamen et al. 2018, Ito et al. 2018, Nabeshima et al. 2018) **height** (Marras et al. 2000, Weston et al. 2018, Koopman et al. 2019a)	**ANOVA** (Marras et al. 2000, Abdoli et al. 2008, Weston et al. 2018, Koopman et al. 2019a, Koopman et al. 2019b) **t-test** (Abdoli et al. 2007) **Wilcoxon signed rank test** (Huysamen et al. 2018, Koopman et al. 2019a) **descriptive statistics** (Ito et al. 2018, Nabeshima et al. 2018)

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Table 2. Summary of proposed assessment method for exoskeletons (Continued 1)

Method	Criterion	Dependent factors	Independent factors	Statistics
Biomechanical analysis	kinetics	**peak estimated waist pressure** (Abdoli et al. 2007) **integrated moment** (Abdoli et al. 2008) **maximal contact pressure** (Huysamen et al. 2018) **peak muscular force** (Weston et al. 2018) **mean muscular force** (Weston et al. 2018)	**style of lifting** (Abdoli et al. 2007, Abdoli et al. 2008, Ito et al. 2018, Koopman et al. 2019b)	
	back strength	**isometric back strength** (Godwin et al. 2009) **endurance time of lifting** (Godwin et al. 2009) **maximal weight lifting** (Baltrusch et al. 2019) **maximal holding time of bending working** (Baltrusch et al. 2019) **maximal holding time of one-hand bank position** (Baltrusch et al. 2019)	**assistance** (Godwin et al. 2009, Baltrusch et al. 2019) **flexion angle** (Baltrusch et al. 2019)**	**ANOVA** (Godwin et al. 2009) **Wilcoxon signed rank test** (Baltrusch et al. 2019)
Physiological evaluation	EMG	**integrated EMG (iEMG)** (Abdoli et al. 2008) **EMG RMS** (Godwin et al. 2009, Tan et al. 2019, Dos Anjos et al. 2022) **EMG median frequency** (Godwin et al. 2009, Dos Anjos et al. 2022, Xiong et al. 2019) **peak normalized EMG (nEMG)** (Ulrey et al. 2013, Lamers et al. 2017, Huysamen et al. 2018, Koopman et al. 2019a) **mean nEMG** (Whitfield et al. 2014, Lamers et al. 2017, Koopman et al. 2019b)	**assistance** (Abdoli et al. 2008, Godwin et al. 2009, Ulrey et al. 2013, Whitfield et al. 2014, Lamers et al. 2017, Huysamen et al. 2018, Koopman et al. 2019a, Koopman et al. 2019b, Tan et al. 2019, Xiong et al. 2019, Dos Anjos et al. 2022) **asymmetry** (Abdoli et al. 2008) **weight** (Abdoli et al. 2008, Ulrey et al. 2013, Lamers et al. 2017, Huysamen et al. 2018) **height** (Koopman et al. 2019a) **style of lifting** (Abdoli et al. 2008, Koopman et al. 2019b) **flexion angle** (Lamers et al. 2017) **lifting phase** (Tan et al. 2019, Dos Anjos et al. 2022) **left or right sides** (Dos Anjos et al. 2022)	**ANOVA** (Abdoli et al. 2008, Godwin et al. 2009, Ulrey et al. 2013, Koopman et al. 2019a, Koopman et al. 2019b, Tan et al. 2019, Dos Anjos et al. 2022) **t-test** (Whitfield et al. 2014, Lamers et al. 2017, Xiong et al. 2019) **Wilcoxon signed rank test** (Huysamen et al. 2018, Koopman et al. 2019a)
	oxygen consumption	**average relative oxygen consumption** (Whitfield et al. 2014) **median metabolic cost of energy** (Xiong et al. 2019)	**assistance** (Whitfield et al. 2014, Xiong et al. 2019)	**t-test** (Whitfield et al. 2014, Xiong et al. 2019)
	heart rate	**normalized heart rage range (HRR)** (Godwin et al. 2009)	**assistance** (Godwin et al. 2009)	**ANOVA** (Godwin et al. 2009)
	task duration	**lifting duration** (Lamers et al. 2017) **carrying duration** (Baltrusch et al. 2019) **sit-to-stand duration** (Baltrusch et al. 2019) **stair-climbing duration** (Baltrusch et al. 2019)	**assistance** (Lamers et al. 2017, Baltrusch et al. 2019) **weight** (Baltrusch et al. 2019)	**t-test** (Lamers et al. 2017) **Wilcoxon signed rank test** (Baltrusch et al. 2019)

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Table 2. Summary of proposed assessment method for exoskeletons (Continued 2)

Method	Criterion	Dependent factors	Independent factors	Statistics
Psychological evaluation	task duration	**ladder climbing duration** (Baltrusch et al. 2019)		
	precision	**kettlebell displacements in lifting** (Lamers et al. 2017) **distance fingertip to the floor in bending** (Baltrusch et al. 2019) **maximal distance between two feet in a wide stance** (Baltrusch et al. 2019)	**assistance** (Lamers et al. 2017, Baltrusch et al. 2019) **weight** (Lamers et al. 2017)	**t-test** (Lamers et al. 2017) **Wilcoxon signed rank test** (Baltrusch et al. 2019)
	qualitative outcomes	**furthest distance in 6-minutes walk** (Baltrusch et al. 2019)	**assistance** (Baltrusch et al. 2019)	**Wilcoxon signed rank test** (Baltrusch et al. 2019)
	subjective comfort	**satisfactory or not** (Abdoli et al. 2008) **rate of perceived exertion (RPE)** (Godwin et al. 2009, Huysamen et al. 2018) **mean Local Perceived Pressure (LPP) score** (Huysamen et al. 2018) **mean System Usability Scale (SUS) score** (Huysamen et al. 2018) **visual-analog scale (VAS) difficulty** (Baltrusch et al. 2019) **VAS scaled discomfort** (Baltrusch et al. 2019) **VAS scaled local discomfort****** (Baltrusch et al. 2019) **perceived VAS** (Tan et al. 2019)	**assistance** (Abdoli et al. 2008, Godwin et al. 2009, Huysamen et al. 2018, Baltrusch et al. 2019, Tan et al. 2019) **weight** (Huysamen et al. 2018) **flexion angle**** (Baltrusch et al. 2019) **style of tasks***** (Baltrusch et al. 2019) **lifting phase** (Tan et al. 2019)	**descriptive statistics** (Abdoli et al. 2008, Huysamen et al. 2018)* **ANOVA** (Godwin et al. 2009, Baltrusch et al. 2019) **Wilcoxon signed rank test** (Huysamen et al. 2018, Baltrusch et al. 2019, Tan et al. 2019)

* For the subjective test, descriptive statistics are for LPP and SUS scores, while the Wilcoxon test is for RPE; ** Flexion angle is only utilized for bending working; *** Lifting, carrying, bending working, one-hand bank position, 6-min walk, sit-to-stand, stair-climbing, ladder climbing, bending, wide stance, rotation, squatting; **** Only utilized for bending working, one-hand bank position tasks, and includes scores of chest, abdomen, upper back, lower back, upper leg front, upper leg back.

compressive force, lumbar shear force, and lumbar moment are difficult to directly obtain by measurement, especially for researchers in the non-medical field, because it involves invasive procedures, for example, inserting pressure sensors directly into the spinal disc. Therefore, these variables are often estimated mechanically with biomechanical simulators. Currently, there are a lot of commercial or open-source software such as AnyBody, 3DSSPP, DhaibaWorks, and OpenSim (Damsgaard et al. 2006, Chaffin 1997, Endo et al. 2014, Delp et al. 2007). In addition, the lumbar assistive torque can also be directly obtained via the assessment method based on the humanoid. As the humanoid is equipped with the exoskeleton instead of humans, the lumbar torque reduction can be measured by the sensors at the humanoid's lumbar joint (Nabeshima et al. 2018, Ito et al. 2018).

When the evaluation criterion was fixed, the statistical methodologies, including the parametric tests (t-test, ANOVA) (Abdoli et al. 2007), a non-parametric test (Wilcoxon test) (Huysamen et al. 2018, Koopman et al. 2019a), and the data dimensions reduction method (PCA) (Sadler et al. 2011) can be employed to compare the safety and effectiveness of exoskeletons under various experimental conditions such as assistance, external load, lifting phase, lifting height, asymmetry, style of task, flexion angle, etc. (Marras et al. 2000, Abdoli et al. 2007, Tan et al. 2019, Koopman et al. 2019a, Baltrusch et al. 2019).

Standards for the assist suit and our evaluation method for dynamic assistive force

1. ISO and JIS standards for the assist suit

Robots that perform useful tasks for humans or equipment, excluding industrial automation applications, are defined as service robots in ISO 13482 (2014). One of them, the restraint-type physical assistant robot, is equivalent to the active type in Table 1. Japan has long been committed to developing standards for service robots and products and took the lead in creating safety requirements for service robots, published as ISO 13482 in 2014. Furthermore, Japan has developed Japanese Industrial Standards (JIS) for low-power active type assist suits, which users can overpower, specifying safety requirements developed from ISO 13482, published as JIS B 8446-2 in 2016 and of them, an assist suit for lumbar assistance specifying safety and performance requirements developed from JIS B 8446-2, published as JIS B 8456-1 in 2017.

JIS B 8456-1 defines the force or torque output by an assist suit as an assistive force to assist the user's intended movement. It describes the simple method for measuring the maximum assistive force, which is a static force or torque, with the assist suit's axis fixed, and a more complex method for measuring how much output torque or lumbar disk compressive force of the user, including dynamic force or torque, is reduced by a humanoid robot. The latter method was established as ISO 18646-4 in 2021, and Japan has long been involved in the evaluation of assist suits utilizing humanoid robots; we summarized the background history of these humanoid robot-based evaluation methods in Japan as follows in our paper (Tanaka et al. 2023). Miura et al. utilized a female humanoid robot to compare the lumbar and hip torques of a robot wearing and not wearing a passive supporter type assist suit and calculated its change over time (Miura et al. 2013). The torque here was estimated from the current value and reduction ratio of the robot's motor with the high-frequency noise removed. Ayusawa et al. estimated the support torque of the assist suit at the lumbar joint from the inertia parameters, motor constants, and reduction ratio of the humanoid robot (Ayusawa et al. 2016). Nabeshima et al. proposed a method to represent the difference in hip joint torque and lumbar compressive force as the assistive torque index (ATI) and lumbar compression reduction (LCR), currently defined in ISO 18646-4, utilizing a humanoid robot that mimics the shape and mass ratio of the human body to when it is wearing and not wearing an assist suit (Nabeshima et al. 2018).

2. Our evaluation method of dynamic assistive force developed from the JIS method

Thus, the methods using humanoid robots instead of real humans to evaluate dynamic assistive force are highly reproducible and has been well-established through a long history of development. Therefore, we have developed a simple and reproducible method for measuring the dynamic assistive force of lumbar support exoskeleton type in agriculture, building on top of the method of measuring static assistive force in JIS B 8456-1 by operating the assist suit while applying a load to it as follows (Tanaka et al. 2023).

Figure 2 illustrates the concept of the measuring method we developed in a polar coordinate system. Given the rotational axis of the assist suit as O, the fixed position where the part of the assist suit on the human thigh is P on the circumference with O as the center. Here, P is connected to resistance by a wire or other means via Q. The resistance is assumed to be at an arbitrary height *h,* and moves vertically *S*. When the assistive force of the assist suit occurs, tension is generated on the wire. By converting this tension into a tangential force at P and multiplying by the radius r_1, the assistive force T is obtained. Therefore, if the angle between OP and PQ is set to θ, the assistive force can be expressed as Equation 1.

$$T = r_1 \times N \times sin\,\theta \tag{1}$$

Here,
T: Assistive force (Nm)
θ: Angle between OP and PQ (rad)
N: Tensile force of line segment PQ (N)
r_1: Distance of OP (mm)
θ can also be expressed in Equation 2.

$$\theta = cos^{-1}\left(\frac{r_2\,cos(\theta_1 - \theta_2) - r_1}{\sqrt{{r_1}^2 + {r_2}^2 - 2r_1r_2\,cos(\theta_1 - \theta_2)}}\right) \tag{2}$$

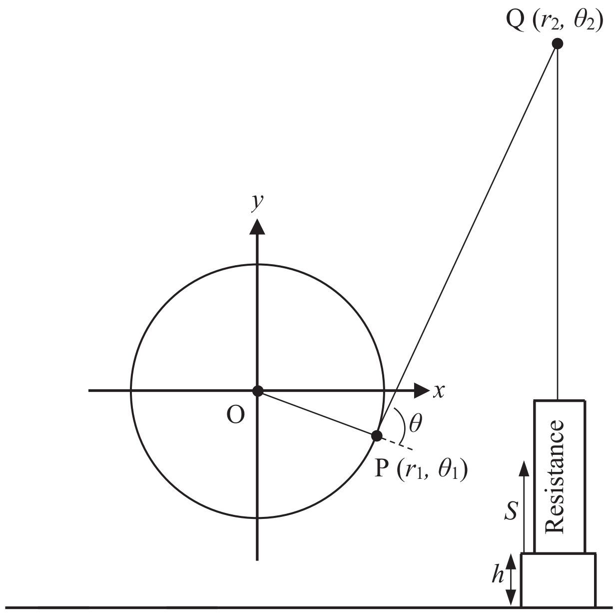

Fig. 2. Concept of measuring dynamic assistive force with polar coordinates system

Then, when the distance between PQ is set to L (mm), the declination angle θ_1 at P is expressed in Equation 3.

$$\theta_1 = -\cos^{-1}\left(\frac{{r_1}^2 + {r_2}^2 - L^2}{2r_1r_2}\right) + \theta_2 \qquad (3)$$

L becomes a minimum when OPQ is located on a straight line and varies with the amount of change in the resistance displacement S (mm). Furthermore, adding an arbitrary height h (mm) to make the initial position of S arbitrary can be expressed as in Equation 4.

$$L = r_2 - r_1 + S + h \qquad (4)$$

Substituting Equation 4 into Equation 3 produces Equation 5.

$$\theta_1 = -\cos^{-1}\left(\frac{{r_1}^2+{r_2}^2-(r_2-r_1+S+h)^2}{2r_1r_2}\right) + \theta_2 \qquad (5)$$

θ_1 can be obtained from S without angle measurement by Equation 5, θ can be obtained from θ_1 by Equation 2, and T can be obtained from θ by Equation 1.

Figure 3 illustrates the measurement equipment developed based on the previous section's dynamic assistive force calculation method. It comprises a fixed pedestal of the assist suit, an electric cylinder, a wire coupled with a load cell, and a pulley. The test preparation becomes easy because Q and h can be calculated backward by obtaining some actual values of θ_1 and S in the stationary state and applying those values and the least-squares method to Equation 5. To subtract the effect of the weight of the assist suit later on, it is recommended to take measurements with the assist suit inactive as well.

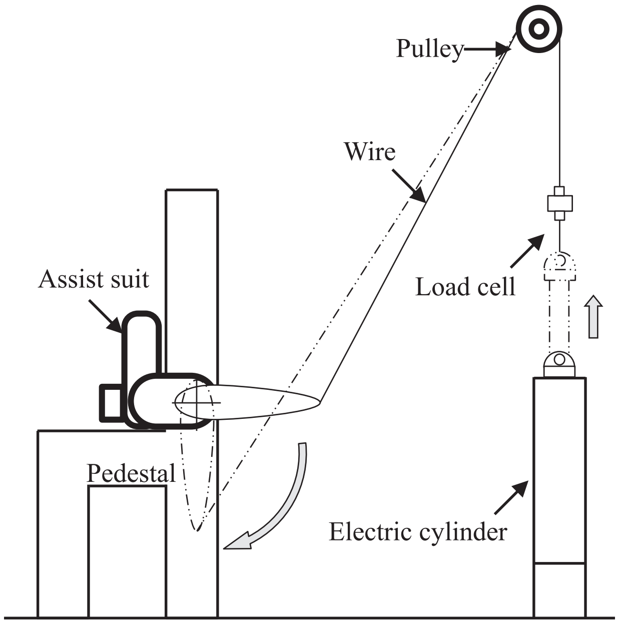

Fig. 3. Dynamic assistive force measurement equipment

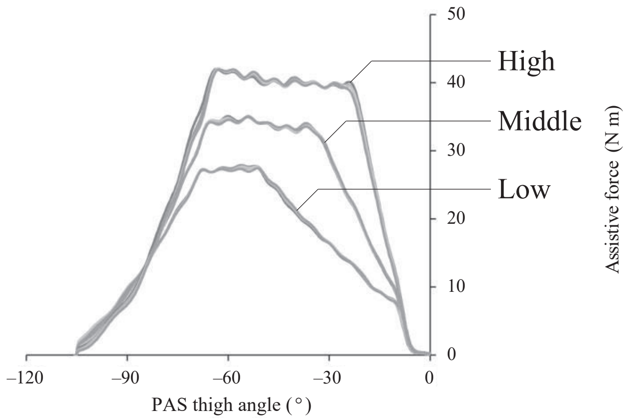

Fig. 4. Dynamic assistive force of exoskeleton-active type (Output on left side)

Figure 4 presents the results of measuring the dynamic assist force of an exoskeleton-active type assist suit with a function to adjust the assistive force to three levels: low, middle, and high, for lifting objects in agricultural applications in Japan utilizing the measurement equipment. The measurements were taken five times in each assist mode, separately for the left and right side, with a sampling period of 1 kHz, and the electric cylinder speed was 250 mm/s. The characteristics of the dynamic assistive force according to the rotational angle were clearly expressed, and the differences in the characteristics in each mode were also presented. The standard deviation of the assistive force at the same rotational angle was 0.2 Nm on average, and the coefficient of variation was at most 0.3% when the average assistive force in the angle range where the maximum assist force was exerted was utilized as the representative value.

Figure 5 presents the results of measuring the dynamic assist force of a commercially available exoskeleton-passive type assist suit equipped with artificial muscles, with the same procedure as in the previous test, but the number of times was 10. The dynamic assistive force according to the rotational angle was clearly expressed in Figure 4.

Based on these results, this measurement method is considered easy to test while having a simple configuration, and the reproducibility of the measured dynamic assist force is reliable.

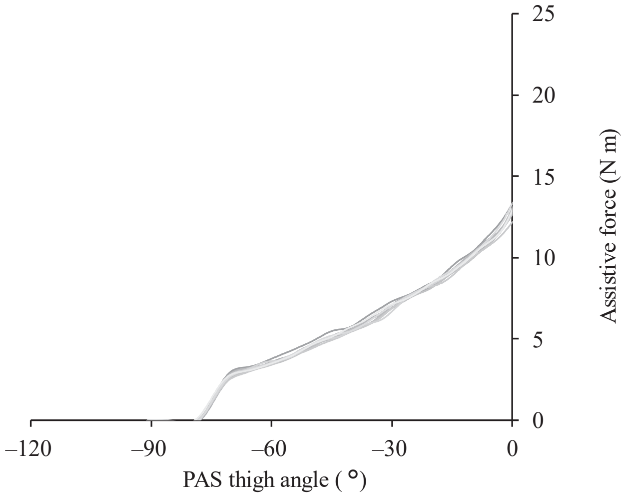

Fig. 5. Dynamic assistive force of exoskeleton-active type (Output on left side)

Reference index of human joints

As described in the previous section, the dynamic assist force obtained can be compared with the allowable values of human joint torques to verify whether the assist suit works safely on humans.

JIS B 8446-2 indicates the maximum exerted forces of the major joints of the human body, which can be referred to in the case the manufacturer does not define the intended user group or estimate them, calculated by multiplying the values of healthy Japanese females aged 75 to 79 (25th percentile) while in isometric exercises obtained by National Institute of Technology and Evaluation (NITE) in Japan and 1.8 which is the coefficient for converting the maximum exerted force from isometric contraction into eccentric contraction of a muscle. Tables 3 and 4 present the maximum major joint exerted force calculated by our statistical processing on the values collected from approximately 1,000 healthy Japanese persons aged 20-80 years by NITE.

Table 3. Maximum major joints exerted force of Japanese male (Unit: N·m)[a]

Joint	Moment (N·m)						Joint angle (deg)
	Extension/Dorsiflexion/Backbending			Flexion/Plantar flexion/Palmar flexion/Forward bending			
	Upper 95% Third quartile	Mean Median	Lower 5% First quartile	Lower 5% First quartile	Mean Median	Upper 95% Third quartile	
Ankle	38.9	27.2	15.6	29.7[b]	47.6[b]	71.3[b]	0
Knee	90.2[b]	72.0[b]	55.2[b]	-	-	-	105
	98.8[b]	78.1[b]	59.6[b]	20.1[b]	27.0[b]	35.3[b]	90
	105.1[b]	82.5[b]	61.3[b]	-	-	-	75
	101.7[b]	79.3[b]	59.7[b]	30.1[b]	41.1[b]	54.2[b]	50
	-	-	-	40.8[b]	56.2[b]	72.2[b]	15
Hip	108.1[b]	65.4[b]	42.1[b]	-	-	-	105
	103.1[b]	61.6[b]	35.9[b]	44.0[b]	55.9[b]	68.0[b]	90
	72.3[b]	43.1[b]	25.8[b]	74.6[b]	92.4[b]	113.9[b]	45
	-	-	-	87.2[b]	110.9[b]	134.7[b]	15
Shoulder	55.4	33.1	10.8	20.6[c]	38.0[c]	55.4[c]	130
	68.0[c]	40.4[c]	12.7[c]	26.6	48.1	69.5	80
	63.6[c]	39.0[c]	14.4[c]	25.0	47.9	70.7	35
Elbow	34.2[c]	22.5[c]	10.9[c]	15.0[c]	33.7[c]	52.5[c]	120
	-	-	-	21.1	40.3	59.5	80
	34.8	20.6	6.4	-	-	-	60
	30.9	18.1	5.4	14.8	30.4	45.9	30
Hand	13.4	8.9	4.3	3.1	9.7	16.3	0

[a] Human Characteristics Database by NITE (FY2001-2002) collected from approximately 500 healthy Japanese males aged 20-80 years old with our original statistical processing.
[b] Evaluated in quartiles because it was not normally distributed
[c] Obvious jump values were excluded.

Table 4. Maximum major joints exerted force of Japanese female (Unit: N·m) [a]

Joint	Moment (N·m)						Joint angle (deg)
	Extension/Dorsiflexion/Backbending			Flexion/Plantar flexion/Palmar flexion/Forward bending			
	Upper 95% Third quartile	Mean Median	Lower 5% First quartile	Lower 5% First quartile	Mean Median	Upper 95% Third quartile	
Ankle	26.84	18.9	11.0	18.2[b]	32.5[b]	45.8[b]	0
Knee	67.4[b]	44.3[b]	21.2[b]	-	-	-	105
	76.6[b]	50.1[b]	23.6[b]	7.2[b]	18.9[b]	30.6[b]	90
	66.4[b]	53.2[b]	40.0[b]	-	-	-	75
	81.1[b]	53.2[b]	25.2[b]	11.4[b]	26.9[b]	42.4[b]	50
	-	-	-	16.1[b]	35.0[b]	54.0[b]	15
Hip	62.1[b]	43.9[b]	32.2[b]	-	-	-	105
	55.1[b]	35.6[b]	25.2[b]	21.6[b]	40.2[b]	58.7[b]	90
	39.0[b]	24.4[b]	14.1[b]	36.6[b]	63.0[b]	89.3[b]	45
	-	-	-	40.1[b]	72.6[b]	105.0[b]	15
Shoulder	27.5	17.6	7.8	14.9[c]	24.1[c]	33.4[c]	130
	34.9[c]	22.0[c]	9.0[c]	19.7	30.4	41.2	80
	34.5[c]	22.0[c]	9.6[c]	18.2	29.6	41.0	35
Elbow	18.9[c]	12.8[c]	6.8[c]	11.7[c]	21.4[c]	31.1[c]	120
	-	-	-	14.0	24.4	34.8	80
	19.7	11.9	4.1	-	-	-	60
	17.0	10.4	3.8	8.8	17.1	25.5	30
Hand	8.8	5.9	3.0	2.4	5.8	9.1	0

[a] Human Characteristics Database by NITE (FY2001-2002) collected from approximately 500 healthy Japanese females aged 20-80 years old with our original statistical processing.
[b] Evaluated in quartiles because it was not normally distributed
[c] Obvious jump values were excluded.

Numerous studies have explored the joint strength of the human body. Table 5 compiles this data, showcasing the human joint strength (N·m) for various joints, such as hand, elbow, shoulder, hip, knee, and ankle, taken from different postures. The data are obtained from 20 distinct studies from 11 countries across Asia, America, Europe, and Africa. The data included males and females aged between 19 and 73 years. The summarized joint strengths are presented as the mean values: hand 5 (3-7), elbow 37.8 (19-69), shoulder 45.2 (26-58), hip 70.7 (44-89), knee 42.3 (21-70), ankle 19.5 (12-29), all in N·m. When comparing the average joint strength from these global studies with the maximum exerted forces of the major joints of the human body as indicated by JIS B 8446-2, which can be referred to in the case of the manufacturer does not define the intended user group or estimate them, similarities are found, and the average values across countries align closely with the NITE JIS B 8446-2 figures. However, a notable variance exists in each joint's strength. Factors such as gender, age, and measurement conditions could account for these differences.

Safe utilization of the assist suit in agriculture

The representative tasks in agriculture that are expected to utilize this assist suit are lifting and transporting objects, holding a half-sit posture, and picking fruits in Japan, as presented in Table 6 from what we have investigated up to now, referring to the form of Annex D in ISO 13482. Table 7 depicts a typical scene of harm an assist suit could cause in agriculture evolved from Annex C of JIS B 8446-2 we developed. In agriculture, work is often done outdoors on sloping or uneven ground with poor footing; in some weather conditions, the ground is wet and slippery. In addition, many obstacles, such as ridges, shores, and ditches, are sometimes climbed over, making falls more likely to occur. Therefore, falls are the most important hazard to be considered in the utilization of assist suits in agriculture.

Table 5. Human joint strength (Unit: N·m) [a]

		Hand	Elbow	Shoulder	Hip	Knee	Ankle	Country	Gender (person)	Age	Condition
1	TMU [b] 2007		45		89			JP	♀	70	90°(elbow), 30°(trunk) (estimated)
2	Okada 1982					70		JP	♀(20)	20-39	15°(knee)
3	Fujiwara 1982						20	JP	♀(7)	70	15°(dorsiflexion)
4	Marsh 1981						29	US	♂(25)	19-37	20°(dorsiflexion)
5	Hagberg 1981			45				SE	♂(6)	18-29	Forward flexion
6	Weston 2018			58				US	♂(31)♀(31)	25 m, 26 f	Turning exertions
7	Hoozemans 2004			26				NL	♂(7)	34	Pushing
8	Ordway 2006					21	12	US	♀(17)	72	Flexion
9	Askew 1987	3	19					US	♀(54)	45	
10	Andrews 1996		26					CA	♀(25)	73	Elbow moment arm= 26.4 cm, wrist moment arm = 6.7cm
11	Balogun 1992		69					Nigeria	♂(64)	23	N to N·m by Kotte 2018 (Based on Askew's moment arm)
12	Douma 2014		47					NL	♂(259) ♀(203)	20-60	N to N·m by Kotte 2018 (Based on Askew's moment arm)
13	Harbo 2012	7	27	31	79	48	17	DK	♀	70	
14	Kramer 1994	5.3						CA	♀(22)	28	Wrist supination
15	Matsuoka 2006	3.8						US	♀(27)	28	Wrist supination
16	Nogueira 2013		45					BR	♂(5)	62	Elbow flexion
17	Timm 1993	5.7						US	♂(10)♀(10)	24-45	Wrist pronation
18	Yang 2014		24					KR	♂(15)♀(15)	24	Elbow extension
19	Cahalan 1989				44			US	♀(16)	53	The average flexion
20	Niu 2012					30		CN	♀(18)	72	Dorsiflexion
Average		5.0	37.8	45.2	70.7	42.3	19.5				
JIS [c]		7.2	32.4	43.2	72	41.4	25.2	JP	♀	75-79	Resting-state

[a] Human strength utilizes the lowest value of adults, usually elderly females. We also include studies that only reported younger age groups.

[b] Tokyo Metropolitan University

[c] The maximum exerted forces of healthy Japanese females aged 75 to 79 (25th percentile) while in isometric exercises obtained by the National Institute of Technology and Evaluation (NITE) were multiplied by 1.8 (the coefficient for converting the maximum exerted force from isometric contraction into eccentric contraction of a muscle).

Table 6. Representative tasks in agriculture

Type of use case	Functional tasks that need to be performed
Lifting and transporting of objects 	Assist in the loading of heavy materials such as harvesting containers, shipping boxes, fertilizer bags, etc. filled with harvested goods on the ground or low to the ground into vehicles, pallets, etc. Assist with basic loading tasks in conditions that involve carrying heavy objects from some distance on the ground that is not necessarily level (flat). Reduce the load on the hips and arms when lifting heavy objects. Examples of heavy objects Collection containers (max. 30 kg) Fertilizer bags (20 kg) Rice bags (30 kg) Examples of platforms Light truck (cargo bed height 65 cm) Agricultural transporter (cargo bed height 50 cm) Pallet
Holding half-sit posture 	Assist in planting seedlings and harvesting crops on the ground or in rows low to the ground. Assist with basic postural holding tasks on ground that is not necessarily level (flat) and with repeated changes from standing to mid-back posture each time planting or harvesting is performed. The task also involves lateral and forward/backward movement between tasks. Reduce the load on the lower back in the mid-back posture. Examples of items handled Seedlings (less than 1 kg) Crops (less than 1 kg) Height range 0 to 30 cm
Holding arm-raising posture for picking fruit 	Assist in picking fruit high off the ground. Assist with basic arm-raising tasks on ground that is not necessarily level (flat) and with repeated changes from a standing position to an arm-raising position each time picking is performed. The task also involves lateral and forward/backward movement between tasks. Reduce the load on the arms in the arm-raising posture. Examples of objects handled Fruits (less than 1 kg)

Table 7. Typical scenes of harm in agriculture

Examples of Harm	Scenes of Harm	Cause	Details of Hazardous Conditions
Fall	Worked on a slope in an orchard, etc. Worked in fields with poor footholds due to rain, etc. Worked on a stepladder or ladder. Worked in heavy rain and strong wind. Stumbled when crossing ridges, footpaths, field entrances (slopes), ditches, irrigation ditches, etc. Worked on the back of a truck or other vehicle or got in or out of a truck or other vehicle.	Use on unstable scaffolds	In the agricultural field, work is done outdoors on sloping or uneven ground with poor footholds, and the ground is wet and slippery depending on the weather. In addition, there are many obstacles such as ridges and ditches to climb over, making falls more likely to occur. The utilization of assistive suits in such an environment may cause falls.
	Unintentional assist force was generated, and stumbled when climbing oversteps and going up and down slopes.	Forgetting to turn off the power	

(Continued on next page)

Table 7. Typical scenes of harm in agriculture (Continued 1)

Examples of Harm	Scenes of Harm	Cause	Details of Hazardous Conditions
Fall	Lifted calves, piglets, and other living creatures.	Inappropriate application	
	Lifted a heavy object that was too heavy or too heavy for the assisting force out of unfamiliarity with the system.	Excessive change in mass of heavy objects due to unexpected assist force	Heavy objects handled in the agricultural field often have inconsistent masses, and unexpected weight changes relative to the assisting force when the user is unfamiliar with the assist suit, may cause falls.
	The device fell and stumbled during utilization owing to improper attachment.	Improper attachment	
	Physical conditions, etc., occur when applied by elderly persons.	Elderly alone outdoors	In the agricultural sector, two-thirds of the workers are elderly people. Because elderly people are expected to utilize the assistive suits alone outdoors, including on slopes, there is a possibility that they may suddenly become ill owing to the outdoor environment or their chronic illnesses may worsen, causing them to mishandle the assistive suit or fall over because of the burden of their body weight.
	The power was turned off, and the device went up and down inclines and steps.	Failure to turn off the power	In the agricultural field, work is done outdoors on sloping or uneven ground with poor footholds, and the ground is wet and slippery depending on the weather. In addition, many obstacles, such as ridges, shores, and ditches, may be climbed over, making it easy for falls to occur. Tipping over may occur owing to the unexpected generation of assist force in such an environment.
	The range of motion of the joints was limited by the large (thigh) frame, etc.; when the robot stumbled while carrying a heavy object, it could not move in time to avoid falling over. Owing to the increased weight of the robot, the user's movement to avoid a fall was delayed longer than usual. The user's unintended generation of assist force caused a delay in avoiding a fall.	Changes in movement to avoid falls due to unexpected limitations in range of motion, increased weight, or assisting forces on unstable footing	In the agricultural field, work is done outdoors on sloping or uneven ground with poor footholds, and the ground is wet and slippery depending on the weather. In addition, many obstacles, such as ridges and ditches that must be climbed over, making it easy for falls to occur. Walking/transportation assistance in such an environment may cause falls due to delayed action to avoid falls when the user stumbles.
	The range of motion of the joints was limited by the upper limb frame, etc., and when the robot stumbled while raising its arms, it could not make a move to avoid falling in time. Owing to the increased weight of the robot, the user's fall-avoidance action was delayed. The user's unintended generation of assist force caused a delay in the fall-avoidance action.	Changes in movement to avoid falls due to unexpected limitations in range of motion, increased weight, or assisting forces on unstable footing	Arm lifting work in the agricultural field is assumed to be fruit harvesting in orchards, which is outdoors on sloping or uneven ground with poor footing, and the ground is often wet and slippery, depending on the weather. In addition, many obstacles, such as fruit residue and stones on the ground, make it easy for falls to occur. With arm-raising assistance in such an environment, falls may occur because of delayed action to avoid falling when the user stumbles.

(Continued on next page)

Table 7. Typical scenes of harm in agriculture (Continued 2)

Examples of Harm	Scenes of Harm	Cause	Details of Hazardous Conditions
Contact	Contact with branches etc. in orchards. Contact with fruits, branches, vines, etc. of vegetables. Contact with a support pole or beam in a greenhouse. Contact with livestock.	Use in environments with many obstacles	In the agricultural field, where many obstacles protrude into the surrounding environment, unintentional contact of the body or rotating parts of the assistive suit with obstacles may cause it to fall over.
Musculoskeletal injury	Used in the rain. Used in dusty or muddy conditions. Corrosion caused by pesticides, fertilizers, manure, etc. Continuous overloading of the motor. Power transmission parts (wires) were damaged due to age-related deterioration or friction. Damaged due to deterioration caused by high/low temperatures or sunlight.	The robot broke down after prolonged utilization in an agricultural environment, rapidly losing assist power.	Because the agricultural sector involves year-round outdoor work, long-term utilization in diverse environments can cause musculoskeletal disorders due to the breakdown of assist suits and sudden loss of assistive force when lifting heavy objects.
Electric shock	Replaced the battery with wet hands. Replaced the battery in the rain or in a damp/wet location.	Electrical short-circuit	In the agricultural field, the surrounding environment is often humid; hence, electric shock is possible due to water droplets adhering to the battery when it is replaced.
Involution	Operated agricultural machinery or equipment while wearing the assistive suit. Operated a transport vehicle while wearing an assistive suit.	Accidents resulting from entrapment in moving parts of the machine or unintended movement of the assistive suit.	In agriculture, people often operate multiple machines and implements in a single day's work. Therefore, operating machines and implements while wearing an assistive suit may cause accidents because the assist suit gets caught in moving parts of the machines and implements or unexpected assistive forces.

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