Biomechanical and Physiological Analyses of a Luggage-Pulling Task

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Abstract: The purpose of this study was to identify the degree of physical stresses on two-wheeled carry-on luggage users in terms of biomechanics and work physiology. Based on 3D kinematics, a 3D inverse dynamic biomechanical model having fifteen segments was developed to evaluate a one-hand pulling task. Joint reaction forces, joint moments and physiological variables (energy expenditure and heart rate) were measured from four subjects who performed 32 luggage-pulling tasks on a doublewide treadmill in the configurations of handle height (100 cm and 110 cm), handle rotation (0° and 90°), pole angle (0° and 10°), wheel diameter (8 cm and 15 cm), load weight (15 kg or 23 kg), center of mass (low and middle), carpeting (no and yes), trial day (first and second) and subject height (short and tall). ANOVA revealed that wheel diameter, center of mass and subject height were highly associated with the physical stresses of luggage users, especially their right arm. Although the task seems light work, users should place heavy belongings at the bottom of luggage when packing and manufacturers should give a priority to large wheels for ergonomic design.

Key words: Pulling task, 3D kinematics, 3D biomechanical model, Work physiology, Ergonomic luggage design

Introduction

Many industries are trying to alleviate a burden of handling materials upon workers by employing high-tech devices, e.g., automated guided vehicles, monorails, conveyers, and cranes. Whether due to economic reasons or due to industrial nature, these are not available in all workplaces. Thus, they still rely on manual vehicles, e.g., wheelbarrows, carts, and hand trucks.

Among these, flight crews often carry two-wheeled luggage, which has never been studied from an ergonomics point of view. It can be easily observed that pulling luggage causes awkward postures of a lateral trunk bending and an asymmetric arm hyperextension. Potential risk factors from such a posture need to be further studied and ergonomic luggage design criteria to be recommended for

reducing physical workload on such users.

In terms of biomechanics and work physiology, the purposes of this study were to identify the degree of physical stresses on luggage users by comparing the diverse configurations of a luggage prototype, and to recommend ergonomic design criteria.

Methods

Subjects

Table 1 summarizes four male subjects who volunteered for the study and were screened for injuries and other physiological problems. All subjects provided informed consent prior to participation in accordance with University Institutional Review Board requirements.

Apparatus

A luggage prototype with the dimension of 56 cm

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Table 1. Anthropometric data and self-selected luggage-pulling speeds

Subject	Age (yr)	Height (cm)	Weight (kg)	Speed (m/s)
1	34	169	68	1.43
2	31	172	67	1.34
3	30	179	70	0.89
4	32	182	78	1.34
Mean (SD)	31.8 (1.7)	175.5 (6.0)	70.8 (5.0)	1.25 (0.24)

(Height) $\times$ 26 cm (Length) $\times$ 46 cm (Width) was made of steel angles and aluminum flat bars. Depending on experimental conditions, the luggage prototype handle height could be adjusted to either 100 cm or 110 cm, the handle could be rotated either 0° or 90°, and the pole angle could be positioned at either 0° (upright) or 10° (bending forward), and hard-rubber wheels were exchanged to be either 8 cm or 15 cm in diameter. A six-component load transducer (PY6-500, Bertec Corporation) was mounted in the pole of the prototype to measure 3D forces. A strip of carpet was wrapped around wheels to simulate a carpeted floor (Fig. 1).

A doublewide treadmill with a running belt of 102 cm $\times$ 145 cm on which luggage was pulled was fabricated with two commercial treadmills (Trimline 7800, HEBB Industries). Two camcorders (DCR-TRV 740, SONY) were placed perpendicular to the sagittal and frontal planes at a distance of 4 m from the treadmill. Videotaped luggage-pulling motion was sampled at 25 Hz with MovieStar 5 (Dazzle DV-Editor, SCM Microsystems). Marker coordinates were manually digitized with Multimedia Video Task Analysis (Version 2.8, Wisconsin Alumni Research Foundation).

Heart rate was measured with a heart rate monitor (Accurex Plus™, Polar Electro). Oxygen uptake in l/min that was later converted to energy expenditure in kcal/min by being multiplied by 4.9 were measured with the MM1 metabolic monitor composed of oxygen analyzer (Model 755, Beckman) and infrared analyzer (Model 864, Beckman)¹¹.

Procedure

After informed of experimental methods, the subject practiced pulling luggage on the treadmill for 5 min at a self-selected walking speed. Nineteen markers were attached to the landmarks^{2, 3}: 1) midpoint between right and left iliac crests, 2) right and 3) left acromia, 4) right and 5) left heads of radius, 6) right and 7) left styloid processes of radius, 8) right and 9) left 3rd knuckles, 10) right and 11) left greater trochanters of femur, 12) right and 13) left condyles of tibia, 14) right and 15) left lateral malleoli, 16) right and 17) left 2nd toes, 18) right top corner of luggage and 19) bottom center of luggage.

Fig. 1. Luggage prototype with the configuration of 110 cm handle height, 90° handle rotation, 10° pole angle, 15 cm wheel diameter, and carpeting. The load of 25 kg was placed at the middle center of mass of luggage.

Given a 5-min break between trials, each subject randomly carried out 32 trials in two days. Each trial took 3 min. Meanwhile, the camcorders captured luggage-pulling motion and the load transducer collected the pulling forces at 25 Hz. Oxygen uptake and heart rate were also read from the monitors. Manual digitized 3D marker coordinates were converted to 3D coordinates about the global reference system by using the formulas of Martin and Pongratz⁴. The second order Butterworth filter in Eq. (1), a recursive digital filter processing raw data in the time domain⁵, was applied forwardly and backwardly with a 5 Hz cutoff frequency to reduce the noise and phase distortion of the coordinates. Then all the necessary kinematic and biomechanical variables were calculated as described in the inverse dynamic biomechanical model section.

$$y(n) = a_0x(n) + a_1x(n-1) + a_2x(n-2) + b_1y(n-1) + b_2y(n-2) \quad (1)$$

where y is filtered data, x is unfiltered data, n is a n th sample, and a_0 , a_1 , a_2 , b_1 , and b_2 are filter coefficients, which were 0.27473, 0.54945, 0.27473, 0.07362, and

-0.17253, respectively.

Inverse dynamic biomechanical model

The kinematics of a whole body with the right hand holding luggage was calculated as an input for a 3D inverse dynamic biomechanical model. The human model was assumed to have 15 rigid segments: 1) head/trunk including head, neck, thorax and abdomen, 2) pelvis, 3) right and 4) left upper arms, 5) right and 6) left forearms, 7) right and 8) left hands, 9) right and 10) left thighs, 11) right and 12) left shanks, 13) right and 14) left feet and 15) luggage. Thus, it had 14 joints whose centers were estimated from marker positions^{2, 6-8}: 1) L₄/L₅, 2) right and 3) left shoulders, 4) right and 5) left elbows, 6) right and 7) left wrists, 8) right and 9) left hips, 10) right and 11) left knees, 12) right and 13) left ankles and 14) luggage handle.

A global reference system, X, Y, and Z, and a local reference systems, x, y, and z, for each segment were employed by a Cartesian coordinate system. The positive directions of the X, Y, and Z axes were anterior, cranial and right lateral, respectively. The local reference system designated the center of mass of each segment as an origin estimated from the joint centers⁹⁻¹¹. The segment angles were calculated with the matrix of direction cosines obtained from vector and matrix algebra of both reference systems. The linear and angular velocities and accelerations were calculated with the Poisson equation and consecutively applied five-point smoothing techniques^{5, 12, 13}. A more detailed description can be found in Jung¹⁴ and Jung *et al.*¹⁵

The mass and inertia tensor, Eq. (2), of each segment were estimated from de Leva⁹ representing them with the ratios of a total body weight and the radius of gyration. The ratios of segment masses to a total body weight were 0.392, 0.112, 0.027, 0.016, 0.006, 0.142, 0.043, and 0.014 for the head/neck, pelvis, upper arm, forearm, hand, thigh, shank, and foot, respectively⁹.

Then the moment of inertia about the global reference system, Eq. (3), was acquired with the matrices of direction cosines for the principle axes of inertia and local reference system, $[R_{PL}]$, and the local reference system and global reference system, $[R_{LG}]$ ¹⁶.

$$\begin{bmatrix} I_X & 0 & 0 \\ 0 & I_Y & 0 \\ 0 & 0 & I_Z \end{bmatrix} = \begin{bmatrix} m(r_x \times l)^2 & 0 & 0 \\ 0 & m(r_y \times l)^2 & 0 \\ 0 & 0 & m(r_z \times l)^2 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} I_{XX} - I_{XY} - I_{XZ} \\ -I_{YX} & I_{YY} - I_{YZ} \\ -I_{ZX} - I_{ZY} & I_{ZZ} \end{bmatrix} = [R_{LG}][R_{PL}] \begin{bmatrix} I_X & 0 & 0 \\ 0 & I_Y & 0 \\ 0 & 0 & I_Z \end{bmatrix} [R_{PL}]^{-1} [R_{LG}]^{-1} \quad (3)$$

where I_X , I_Y , and I_Z are the principle moments of inertia associated with the principle axes of inertia about the center of mass of a segment, m is a segment mass, r_x , r_y , and r_z are the radii of gyration, l is a segment length, and I_{XX} , I_{XY} , I_{XZ} , I_{YX} , I_{YY} , I_{YZ} , I_{ZX} , I_{ZY} , and I_{ZZ} are the components of the moment of inertia.

The equations of motion were developed to describe both linear and rotational motion of a segment with the Newtonian mechanics under the assumption that all forces acted on the joint center or tip of a segment. If the segment i was adjoined with n segments, there were n joint reaction forces and thus the force equation for the segment i about its center of mass followed the Newton's second law seen in Eq. (4)⁵. Along with n joint reaction forces, there were also n moments. The moment equation followed the moment-angular momentum relationship seen in Eq. (5)¹⁷.

$$\sum_{j=1}^n [F_j] + m[g] = m[a] \quad (4)$$

$$\sum_{j=1}^n [M_j] + \sum_{j=1}^n [(P_j - P_{CM})F_j] = \frac{d}{dt}h \quad (5)$$

where $[F_j]$ is a joint reaction force matrix at the joint center j , m is a mass, $[g]$ is a gravitational acceleration matrix, $[a]$ is a linear acceleration matrix, $[M_j]$ is a moment matrix at the joint center j , P_j is the position of the joint center j , P_{CM} is the center of mass, and dh/dt is the angular momentum.

Experiment design

To reduce the total number of trials to 64 (32 trials for every short subject and 32 trials for every tall subject)¹⁸, a 2^{9-3} fractional factorial design was used instead of a full factorial design which would require 256 trials for every short subject and 256 trials for every tall subject. The ANOVA analysis of the fractional factorial allowed only the main effects of handle height (100 cm and 110 cm), handle rotation (0° and 90°), pole angle (0° and 10°), wheel diameter (8 cm and 15 cm), load weight (15 kg and 23 kg), center of mass (low and middle), carpeting (no and yes), trial day (first and second), and subject height (short and tall) as independent variables to be examined. Tables 2 and 3 show the arrangements of all trials for short and tall subjects. Discrimination between short and tall subjects administered the 50th percentile US HEW male height of 175 cm¹⁹. When load was placed at the bottom of and in the middle of luggage that were arbitrarily selected by the experimenter for experimental design purposes, the centers of mass of luggage were located at 20% (Low) and 31% (Middle) of luggage length from the ground. The bare wheels and the wheels wrapped with a strip of carpet were used to simulate a

Table 2. Trial arrangement of nine independent variables for short subjects

Trials	Independent variables							
	Handle height	Handle rotation	Pole angle	Wheel diameter	Load weight	Center of mass	Carpeting	Trial day
1	100 cm	0°	0°	8 cm	15 kg	Low	No	First
2	100 cm	0°	10°	15 cm	15 kg	Low	No	First
3	100 cm	90°	0°	15 cm	15 kg	Low	No	First
4	100 cm	90°	10°	8 cm	15 kg	Low	No	First
5	110 cm	0°	0°	15 cm	15 kg	Low	No	First
6	110 cm	0°	10°	8 cm	15 kg	Low	No	First
7	110 cm	90°	0°	8 cm	15 kg	Low	No	First
8	110 cm	90°	10°	15 cm	15 kg	Low	No	First
9	100 cm	0°	0°	8 cm	15 kg	Middle	Yes	First
10	100 cm	0°	10°	15 cm	15 kg	Middle	Yes	First
11	100 cm	90°	0°	15 cm	15 kg	Middle	Yes	First
12	100 cm	90°	10°	8 cm	15 kg	Middle	Yes	First
13	110 cm	0°	0°	15 cm	15 kg	Middle	Yes	First
14	110 cm	0°	10°	8 cm	15 kg	Middle	Yes	First
15	110 cm	90°	0°	8 cm	15 kg	Middle	Yes	First
16	110 cm	90°	10°	15 cm	15 kg	Middle	Yes	First
17	100 cm	0°	0°	8 cm	23 kg	Low	Yes	Second
18	100 cm	0°	10°	15 cm	23 kg	Low	Yes	Second
19	100 cm	90°	0°	15 cm	23 kg	Low	Yes	Second
20	100 cm	90°	10°	8 cm	23 kg	Low	Yes	Second
21	110 cm	0°	0°	15 cm	23 kg	Low	Yes	Second
22	110 cm	0°	10°	8 cm	23 kg	Low	Yes	Second
23	110 cm	90°	0°	8 cm	23 kg	Low	Yes	Second
24	110 cm	90°	10°	15 cm	23 kg	Low	Yes	Second
25	100 cm	0°	0°	8 cm	23 kg	Middle	No	Second
26	100 cm	0°	10°	15 cm	23 kg	Middle	No	Second
27	100 cm	90°	0°	15 cm	23 kg	Middle	No	Second
28	100 cm	90°	10°	8 cm	23 kg	Middle	No	Second
29	110 cm	0°	0°	15 cm	23 kg	Middle	No	Second
30	110 cm	0°	10°	8 cm	23 kg	Middle	No	Second
31	110 cm	90°	0°	8 cm	23 kg	Middle	No	Second
32	110 cm	90°	10°	15 cm	23 kg	Middle	No	Second

carpeting effect (Fig. 1).

Dependent variables were joint reaction force and moment at each joint along *X*, *Y*, and *Z* axes, energy expenditure, and heart rate. The averaged values of joint reaction forces and moments were used during the 3-min trials with an interval of approximately 2.6 s. Analyses of variance (ANOVA) were applied to find only significant main effects of independent variables with SPSS Release 13.0 (SPSS Inc.).

Results

Joint reaction forces

The joints of the right arm and handle were mainly

affected by handle height, pole angle, wheel diameter, center of mass, and carpeting. Though statistically significant, additionally, the main effects of handle height, pole angle and carpeting were smaller than 10 N in terms of mean differences between the levels of each variables.

The 110 cm handle, 10° pole and middle center of mass increased the reaction forces along the *X* axis, but about the *Y* axis they were decreased with the 10° pole and increased with the middle center of mass. The 15 cm wheels influenced the reaction forces of all three axes, decrement on the *X* and *Y* axes but increment on the *Z* axis. The load of 23 kg had the opposite results for the *X* and *Y* axes of the right arm and increased the reaction forces of the right leg joints along the *Z* axis. The car-

Table 3. Trial arrangement of nine independent variables for tall subjects

Trials	Independent variables							Trial day
	Handle height	Handle rotation	Pole angle	Wheel diameter	Load weight	Center of mass	Carpeting	
1	100 cm	0°	0°	8 cm	15 kg	Low	Yes	Second
2	100 cm	0°	10°	15 cm	15 kg	Low	Yes	Second
3	100 cm	90°	0°	15 cm	15 kg	Low	Yes	Second
4	100 cm	90°	10°	8 cm	15 kg	Low	Yes	Second
5	110 cm	0°	0°	15 cm	15 kg	Low	Yes	Second
6	110 cm	0°	10°	8 cm	15 kg	Low	Yes	Second
7	110 cm	90°	0°	8 cm	15 kg	Low	Yes	Second
8	110 cm	90°	10°	15 cm	15 kg	Low	Yes	Second
9	100 cm	0°	0°	8 cm	15 kg	Middle	No	Second
10	100 cm	0°	10°	15 cm	15 kg	Middle	No	Second
11	100 cm	90°	0°	15 cm	15 kg	Middle	No	Second
12	100 cm	90°	10°	8 cm	15 kg	Middle	No	Second
13	110 cm	0°	0°	15 cm	15 kg	Middle	No	Second
14	110 cm	0°	10°	8 cm	15 kg	Middle	No	Second
15	110 cm	90°	0°	8 cm	15 kg	Middle	No	Second
16	110 cm	90°	10°	15 cm	15 kg	Middle	No	Second
17	100 cm	0°	0°	8 cm	23 kg	Low	No	First
18	100 cm	0°	10°	15 cm	23 kg	Low	No	First
19	100 cm	90°	0°	15 cm	23 kg	Low	No	First
20	100 cm	90°	10°	8 cm	23 kg	Low	No	First
21	110 cm	0°	0°	15 cm	23 kg	Low	No	First
22	110 cm	0°	10°	8 cm	23 kg	Low	No	First
23	110 cm	90°	0°	8 cm	23 kg	Low	No	First
24	110 cm	90°	10°	15 cm	23 kg	Low	No	First
25	100 cm	0°	0°	8 cm	23 kg	Middle	Yes	First
26	100 cm	0°	10°	15 cm	23 kg	Middle	Yes	First
27	100 cm	90°	0°	15 cm	23 kg	Middle	Yes	First
28	100 cm	90°	10°	8 cm	23 kg	Middle	Yes	First
29	110 cm	0°	0°	15 cm	23 kg	Middle	Yes	First
30	110 cm	0°	10°	8 cm	23 kg	Middle	Yes	First
31	110 cm	90°	0°	8 cm	23 kg	Middle	Yes	First
32	110 cm	90°	10°	15 cm	23 kg	Middle	Yes	First

peted floor increased the forces of the right arm joints along the *Y* and *Z* axes. All the segments excluding the left arm were affected by subject height. The tall subjects had smaller reaction forces on the *X* axis but larger forces on the *Z* axis than the short subjects (Table 4).

Joint moments and physiological variables

Seen in Tables 5 and 6, the consequences of the joint moments and physiological variables were rather simpler than those of the reaction forces. The load of 23 kg increased the moments of the L_4/L_5 and leg joints on the *X* axis. The tall subjects had larger moments at the right shoulder and L_4/L_5 along the *X* and *Z* axes than the short subjects.

The load of 23 kg and second day of trial required more energy expenditure and heart rate, while the 15 cm wheels required less energy expenditure.

Discussion

The 110 cm handle increased the reaction forces at the right arm and handle joints by 15% because the subject could pay more attention to pulling luggage forward with a long handle. It agreed with the stability of the long handle of a two-wheeled cylinder hand truck found by Okunribido and Haslegrave²⁰⁾ because of the reduction of sideward movement. However, reaction force differences between two handle height conditions were so small, less

Table 4. ANOVA of significant independent variables for joint reaction forces

Independent variables	Joints	Axes	Mean $\pm$ SD (N)	
			Low	High
Handle height	Right shoulder	X**	19.9 $\pm$ 12.2	23.2 $\pm$ 12.2
	Right elbow	X**	19.6 $\pm$ 12.6	22.9 $\pm$ 12.5
	Right wrist	X**	20.6 $\pm$ 12.8	23.5 $\pm$ 12.7
	Handle	X**	21.1 $\pm$ 12.9	23.9 $\pm$ 12.8
Pole angle	Right shoulder	X**	20.1 $\pm$ 11.5	23.1 $\pm$ 12.9
	Right elbow	X**	19.5 $\pm$ 12.1	23.0 $\pm$ 12.9
	Right wrist	Y**	35.3 $\pm$ 17.3	29.7 $\pm$ 14.0
		X**	20.2 $\pm$ 12.4	23.8 $\pm$ 13.0
	Handle	Y**	47.2 $\pm$ 17.2	41.2 $\pm$ 15.6
		X**	20.7 $\pm$ 12.5	24.3 $\pm$ 13.1
		Y**	52.0 $\pm$ 17.3	46.0 $\pm$ 16.0
		X**	23.0 $\pm$ 12.5	20.1 $\pm$ 11.9
Wheel diameter	Right shoulder	Z*	7.3 $\pm$ 2.4	8.2 $\pm$ 3.7
		X**	22.8 $\pm$ 13.0	19.7 $\pm$ 12.1
	Right elbow	Y**	40.5 $\pm$ 14.7	24.5 $\pm$ 12.7
		Z**	5.2 $\pm$ 2.3	6.6 $\pm$ 4.0
	Right wrist	X**	23.7 $\pm$ 13.1	20.4 $\pm$ 12.3
		Y**	53.0 $\pm$ 14.4	35.4 $\pm$ 13.9
		Z**	5.2 $\pm$ 2.3	6.6 $\pm$ 4.0
	Handle	X**	24.2 $\pm$ 13.2	20.8 $\pm$ 12.4
		Y**	58.0 $\pm$ 14.5	40.0 $\pm$ 14.0
		Z**	5.5 $\pm$ 2.3	6.8 $\pm$ 3.8
	Right shoulder	X**	18.2 $\pm$ 8.6	24.9 $\pm$ 14.4
		Y**	23.2 $\pm$ 6.4	29.8 $\pm$ 11.9
Load weight	Right elbow	X**	17.8 $\pm$ 8.5	24.7 $\pm$ 15.0
		Y**	25.6 $\pm$ 10.6	39.4 $\pm$ 17.3
	Right wrist	X**	18.5 $\pm$ 8.4	25.6 $\pm$ 15.3
		Y**	37.6 $\pm$ 10.9	50.8 $\pm$ 18.8
	Handle	X**	18.8 $\pm$ 8.4	26.1 $\pm$ 15.3
		Y**	42.5 $\pm$ 11.0	55.5 $\pm$ 19.1
	Right hip	Z*	56.2 $\pm$ 14.2	62.5 $\pm$ 19.8
	Right knee	Z*	61.1 $\pm$ 17.1	68.2 $\pm$ 23.0
	Right ankle	Z*	60.8 $\pm$ 17.4	68.0 $\pm$ 22.9

* Significant difference at $p < 0.05$, ** Significant difference at $p < 0.01$.

than 3.4 N, that joint moments and physiological variables were not significant.

The 10° pole required 12% less downward force at the handle than the 0° pole, and so decreased the vertical reaction forces at the right arm. Kingma *et al.*²¹⁾ also found a similar result with a two-wheeled trash container. The projection length of the distance between the center of mass and axle on the ground, i.e. moment arm, was shorter for the 10° pole than for the 0° pole because the 10° pole luggage was more erect than the 0° pole luggage. Therefore, the 10° pole luggage leaned forward less due to a smaller flexion moment in the sagittal plane which resulted in the subject pulling the luggage more forward with 17% more force.

The 15 cm wheels required lower forward and downward forces by 14% and 31%, respectively, and more sideward force by 24% than the 8 cm wheels. Thus, the corresponding reaction forces at the right arm accordingly decreased or increased. Additionally, the 15 cm wheels required 6% less energy expenditure. It is well known that large wheels reduce physical stress on a user of operating manual vehicles^{22–26)}. Al-Eisawi *et al.*²⁶⁾ calculated the coefficients of rolling friction between wheels and several floor types with Eq. (6). The radius of wheels is in inverse proportion to an external force in the conditions of constant rolling friction and weight. The coefficients of rolling friction between two wheel size conditions in this study can be considered similar because iden-

Table 4. ANOVA of significant independent variables for joint reaction forces (cont.)

Independent variables	Joints	Axes	Mean $\pm$ SD (N)	
			Low	High
Center of mass	Right shoulder	X**	11.2 $\pm$ 3.5	31.9 $\pm$ 8.6
	Right elbow	X**	10.7 $\pm$ 3.6	31.8 $\pm$ 8.9
		Y**	24.2 $\pm$ 10.6	40.8 $\pm$ 16.0
	Right wrist	X**	11.3 $\pm$ 3.8	32.8 $\pm$ 9.0
		Y**	35.4 $\pm$ 12.1	53.0 $\pm$ 16.0
	Handle	X**	11.7 $\pm$ 3.8	33.2 $\pm$ 9.1
Carpeting		Y**	40.1 $\pm$ 12.3	57.9 $\pm$ 16.1
	Right shoulder	Z**	5.7 $\pm$ 1.3	9.8 $\pm$ 3.1
	Right elbow	Y*	31.1 $\pm$ 15.6	33.9 $\pm$ 16.1
		Z**	3.5 $\pm$ 1.1	8.4 $\pm$ 3.0
	Right wrist	Y**	42.3 $\pm$ 16.5	46.1 $\pm$ 16.8
		Z**	3.5 $\pm$ 1.0	8.3 $\pm$ 3.0
Subject height	Handle	Y**	47.0 $\pm$ 16.6	51.0 $\pm$ 16.9
		Z**	3.8 $\pm$ 1.1	8.5 $\pm$ 2.9
	Right shoulder	X**	23.5 $\pm$ 12.8	19.6 $\pm$ 11.4
	Right elbow	X**	23.3 $\pm$ 13.1	19.2 $\pm$ 11.8
	Right wrist	X**	24.2 $\pm$ 13.3	19.9 $\pm$ 12.0
	L ₄ /L ₅	X**	78.4 $\pm$ 14.5	68.8 $\pm$ 13.7
		Z**	54.7 $\pm$ 9.8	65.5 $\pm$ 16.6
	Right hip	X**	117.6 $\pm$ 15.1	102.6 $\pm$ 26.6
		Z**	53.0 $\pm$ 13.5	65.7 $\pm$ 18.6
	Right knee	X**	117.5 $\pm$ 26.5	96.5 $\pm$ 19.7
		Z**	58.5 $\pm$ 16.4	70.8 $\pm$ 22.4
	Right ankle	X**	141.8 $\pm$ 26.8	108.8 $\pm$ 22.5
		Z**	59.3 $\pm$ 17.2	69.5 $\pm$ 22.6
	Left hip	X*	137.8 $\pm$ 19.5	127.9 $\pm$ 29.1
		Z**	52.5 $\pm$ 14.5	69.9 $\pm$ 20.8
	Left knee	X**	116.2 $\pm$ 21.1	100.5 $\pm$ 26.6
		Z**	57.6 $\pm$ 16.1	75.8 $\pm$ 23.1
	Left ankle	X**	131.6 $\pm$ 23.1	102.9 $\pm$ 31.1
		Z**	57.3 $\pm$ 16.4	74.3 $\pm$ 23.4
	Handle	X**	24.7 $\pm$ 13.4	20.2 $\pm$ 12.0

* Significant difference at $p < 0.05$, ** Significant difference at $p < 0.01$.

tical wheel materials used on one type of the running belt. The moment of inertia difference between two conditions might be also negligible because the subject pulled luggage at a constant walking speed set by the treadmill.

$$F = \rho \frac{W}{r} \quad (6)$$

where F is an external force, ρ is the coefficient of rolling friction, W is weight, and r is a wheel radius.

Load weight was significant for all three dependent variables and affected all the segments except the left arm. It agreed with other studies^{27–33}). The reaction forces in the forward and downward directions at the right arm and handle joints noticeably increased by 39% and 30% with 23 kg. It also increased the sideward reaction forces and

lateral-bending moments of the head/trunk and legs. Pulling the load of 23 kg required more energy expenditure and heart rate of 8% and 5%, respectively, than that of 15 kg. In other words, 33 cal/min were used and 0.64 bpm increased per kg when pulling luggage.

It was consistent that the middle center of mass of luggage increased the downward force by 44% and forward pulling force by 184% at the handle joint than the low center of mass. The similar situations could be observed at the right arm joints.

Large physical workloads are required when manual vehicles are maneuvered on a carpeted floor due to large rolling friction between wheels and the floor^{23, 26, 31, 34}). In this study, the downward and sideward reaction forces increased at the right arm and handle joints on the car-

Table 5. ANOVA of significant independent variables for joint moments

Independent variables	Joints	Axes	Mean $\pm$ SD (Nm)	
			Low	High
Load weight	L ₄ /L ₅	X**	103.4 $\pm$ 20.4	111.0 $\pm$ 19.8
	Right hip	X*	72.7 $\pm$ 15.1	78.8 $\pm$ 14.2
	Right ankle	X**	64.1 $\pm$ 14.2	69.7 $\pm$ 9.6
	Left hip	X*	72.1 $\pm$ 16.4	78.4 $\pm$ 15.1
	Left knee	X*	31.7 $\pm$ 12.9	35.8 $\pm$ 10.1
Subject height	Right shoulder	X*	9.6 $\pm$ 7.8	15.4 $\pm$ 21.0
	L ₄ /L ₅	X**	94.4 $\pm$ 11.9	120.0 $\pm$ 19.1
		Z*	109.4 $\pm$ 16.4	128.8 $\pm$ 64.4

* Significant difference at $p < 0.05$, ** Significant difference at $p < 0.01$.

Table 6. ANOVA of significant independent variables for physiological variables

Dependent variables	Independent variables	Mean $\pm$ SD (kcal/min, bpm)	
		Low	High
Energy expenditure	Wheel diameter*	3.26 $\pm$ 0.49	3.07 $\pm$ 0.42
	Load weight**	3.04 $\pm$ 0.32	3.30 $\pm$ 0.55
	Trial day**	3.01 $\pm$ 0.44	3.32 $\pm$ 0.44
Heart rate	Load weight**	96.7 $\pm$ 5.89	101.8 $\pm$ 12.38
	Trial day**	96.7 $\pm$ 9.05	101.9 $\pm$ 10.27

* Significant difference at $p < 0.05$, ** Significant difference at $p < 0.01$.

peted floor. However, their effects seem small enough not to be considered because luggage was already in motion.

Though each subject used the exactly same self-selected walking speed on both days, trial day was significant for physiological variables. It could be speculated, according to the results, that a training effect might have occurred between the trial days. Since trial day could not inherently controlled by randomization in the experimental design, this training effect could have been reduced if sufficient practice time of more than 5 min, that were adopted in this study, were allowed to the subject before the experiment.

Subject height influenced the greatest number of segments. The short subjects had large joint reaction forces in the forward direction but small forces in the sideward direction, while the tall subjects had large moments at the right shoulder and L₄/L₅ joints. Selecting the faster luggage-pulling speed than the tall subjects, the short subjects might more concentrate on forward and backward movement than sideward to keep up the speed of the running belt. The speed of handling manual vehicles is directly proportional to physical workload^{23, 32, 35, 36}. Even 110 cm handle height that is longer than that of commercially available luggage may not be long enough for the tall subjects to have a natural posture during a luggage-pulling task. Okunribido and Haslegrave²⁰ and

Kingma *et al.*²¹) found that two-wheeled cart operators kept a certain height of the handle grip regardless of the knuckle and handle heights without trying to adjust it to reduce physical stresses. Since this relatively short handle height with respect to the tall subjects did not provide enough clearance between the legs and luggage to avoid heel-kicking of luggage, it might induce an awkward posture resulting in large moments in the shoulder and trunk. Kingma *et al.*²¹), Jäger *et al.*³⁰), and Lee *et al.*³⁵) also found that tall and heavy operators generally showed larger moments at the lower back than short and light operators when handling manual vehicles.

This study was performed as a pilot study for a series of research studies to examine the safety of airline workers such as pilots, flight crews, and luggage handlers who frequently deal with luggage for occupational purposes. The 3D biomechanical model was developed for a one-hand pulling task, which can be applicable to other tasks such as carrying or holding a material with one hand. However, it should be validated over all these other tasks, and ground reaction forces directly measured from force plates would be potential data to be used for the validation by comparing with ground reaction forces calculated from the model. Another limitation of this study is that the data of only four subjects were utilized for statistical analyses. Though general notions can be given on the relationship between luggage design and user's physical

stress, it had insufficient statistical power to significantly discriminate the main effects of the independent variables and more subjects are needed for convincing generalizations.

In conclusion, a luggage-pulling task mainly stresses the right arm and is classified as "light work" by the criterion of American Industrial Hygiene Association¹⁾ because it needed only 3.2 kcal/min of metabolic energy and 99.3 bpm of heart rate on average. Subject height and related walking speed is of importance to the task and heavy belongings should be placed at the bottom of luggage when packing. Large wheels are prior to handle height, pole angle and handle rotation for an ergonomic luggage design.

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