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**Luggage-Pulling Task Evaluation by
Kinematics and Subjective Ratings**

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Bio-Sketches

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Abstract

A wheeled luggage-pulling task was evaluated in terms of kinematics and perceived exertion to identify the degree of physical load on luggage users. The main effects of 9 independent variables (handle height, handle rotation, pole angle, wheel diameter, load weight, center of mass, carpeting, trial day, and subject height) were tested on 141 dependent variables by developing a 15 segment kinematic model. Four male students volunteered to randomly perform 32 luggage-pulling tasks on a treadmill. The results of MANOVA and ANOVA revealed that the 110 cm handle and a 10° pole influenced the kinematics of luggage such that it provided more clearance for the right leg. The 90° rotated handle resulted in a neutral hand posture and was of advantage to luggage stability. 15 cm wheels allowed a more natural motion of the right arm, and the 23 kg load and the middle position for the luggage center of mass increased perceived exertion especially in the right arm. Carpeting was not significant due to the inappropriate imitation of carpeting environment or a training effect that the subject can become used to the experimental method of pulling luggage on the treadmill on the second day of the testing. Subject height along with luggage-pulling speed was the most significant variable, affecting all body part kinematics. Conclusively, pulling luggage is considered to be light work with moderate stress on users.

Keywords: Luggage pulling task; Luggage design; Kinematic model



1. Introduction

Manual vehicles, such as carts, hand trucks, wheelbarrows, etc., have been of great advantage to the transportation of materials due to the presence of wheels. Over decades, many studies have shown that the use of manual vehicles is less stressful and more efficient than their nonuse in manual material handlings (Banerjee et al., 1959; Haisman et al., 1972; Jäger et al., 1984; Schibye et al., 2001).

One of the most popular manual vehicles is carry-on style two-wheeled luggage used by flight crews and travelers. However, the research literature shows that such luggage has never been studied from an ergonomics standpoint. Since a luggage-pulling task often results in awkward postures such as an asymmetrical and hyper-extended arm and a laterally bent trunk, potential risk factors need to be studied.

Therefore, the objective of this study was to identify the extent of the physical load on luggage users and to recommend luggage design criteria by comparing a different configuration of a carry-on luggage prototype under various conditions from a kinematics and a subjective rating standpoint.

This study begins with the explanation of a kinematic model development and then experimental methods to test luggage-pulling motion on a treadmill. In terms of peak angle, peak linear acceleration, peak angular acceleration, and subjective ratings of each body part in this order as the dependent variables of statistical analyses, the findings are summarized in the results section with eight tables. Finally, the significances of handle height, handle rotation, pole angle, wheel diameter, load weight, center of mass, carpeting, trial day, and subject height on the



variables are discussed and then luggage design guidelines are suggested in the conclusions section.

2. Kinematic method

The following procedure was used to obtain the 3D kinematics of a whole body including luggage with two standard camcorders. The human model was assumed to consist of 15 segments: 1) head/trunk, 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. The head/trunk included head, neck, thorax and abdomen (Fig. 1).

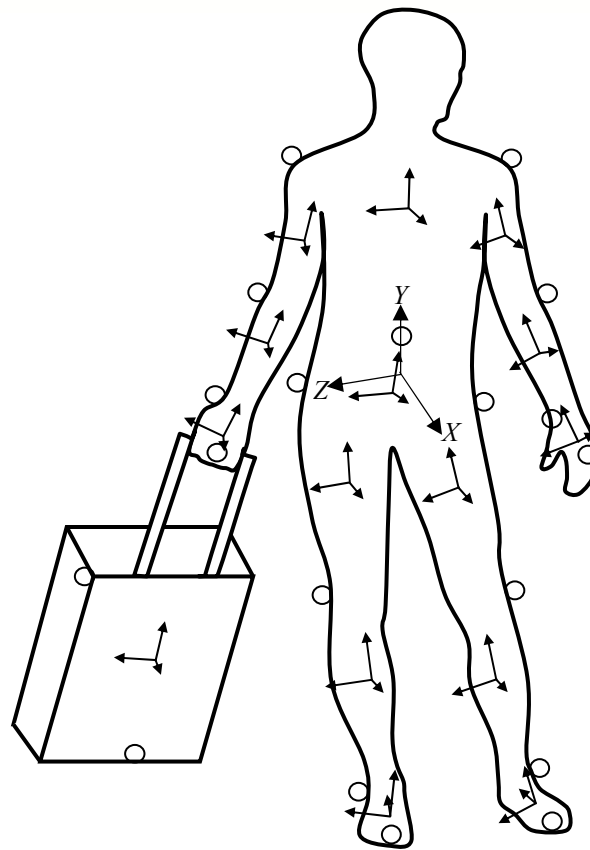


Fig. 1. Human model with space frame (large arrows with the letters of X , Y and Z), segment frames (small arrows) and markers (circles)

The space frame, X , Y , and Z , was employed to locate the segments in space. Its origin was positioned at the center of a captured video frame. The positive directions of the X , Y , and Z axes were anterior, cranial, and right lateral, respectively (Winter, 1990).

Nineteen markers were attached to the landmarks (De Leva, 1996b; McConville et al., 1980): 1) midpoint between right and left iliac crests, 2) right and 3) left acromia, 4) right and 5) left heads of radii, 6) right and 7) left styloid processes of radii, 8) right and 9) left third knuckles, 10) right and 11) left greater trochanters of femurs, 12) right and 13) left condyles of tibiae, 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. Using the Martin and Pongratz's formulas (1974) after scaling, the marker coordinates extracted from the video clips were converted to the coordinates about the space frame.

The positions of fourteen joints, 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) handle, were approximated from the marker positions (Seidel et al., 1995; De Leva, 1996b; Veeger, 2000; Skotte, 2001). The centers of masses of the segments were then estimated based on the joint positions (Dempster, 1955; De Leva, 1996a; Plangenhoeft et al., 1983). The center of mass of luggage was directly measured with a balance technique.

Designating the center of mass as an origin, each segment frame, x , y , and z , which moved with the segment was determined by the center of mass, proximal joint, and proximal marker. The positive direction of the y axis was defined as the relative position of the proximal joint with respect to the center of mass. The midpoint between right and left shoulders and L₄/L₅ were used for the head/trunk and pelvis, respectively. The x axis whose positive direction was anterior was obtained by the cross product of the y axis and the relative position of the proximal marker with respect to the center of mass. The z axis whose positive direction was right lateral was obtained by the cross product of the x and y axes. After dividing their own magnitudes to make them unit vectors, each of the nine components, three for each axis, formed the matrix of direction cosines that represented the rotational relationship between the segment frame and the space frame at time t seen in Equation 1 (Zatsiorsky, 1998).

$$\begin{bmatrix} \cos_{Xx}(t) & \cos_{Xy}(t) & \cos_{Xz}(t) \\ \cos_{Yx}(t) & \cos_{Yy}(t) & \cos_{Yz}(t) \\ \cos_{Zx}(t) & \cos_{Zy}(t) & \cos_{Zz}(t) \end{bmatrix}$$



$$= \begin{bmatrix} \frac{Xx(t)}{(Xx(t)^2 + Yx(t)^2 + Zx(t)^2)^{1/2}} & \frac{Xy(t)}{(Xy(t)^2 + Yy(t)^2 + Zy(t)^2)^{1/2}} & \frac{Xz(t)}{(Xz(t)^2 + Yz(t)^2 + Zz(t)^2)^{1/2}} \\ \frac{Yx(t)}{(Xx(t)^2 + Yx(t)^2 + Zx(t)^2)^{1/2}} & \frac{Yy(t)}{(Xy(t)^2 + Yy(t)^2 + Zy(t)^2)^{1/2}} & \frac{Yz(t)}{(Xz(t)^2 + Yz(t)^2 + Zz(t)^2)^{1/2}} \\ \frac{Zx(t)}{(Xx(t)^2 + Yx(t)^2 + Zx(t)^2)^{1/2}} & \frac{Zy(t)}{(Xy(t)^2 + Yy(t)^2 + Zy(t)^2)^{1/2}} & \frac{Zz(t)}{(Xz(t)^2 + Yz(t)^2 + Zz(t)^2)^{1/2}} \end{bmatrix} \quad (1)$$

where $Xx(t)$, $Yx(t)$, and $Zx(t)$, $Xy(t)$, $Yy(t)$, and $Zy(t)$, and $Xz(t)$, $Yz(t)$, and $Zz(t)$ are the relative coordinates of the x , y , and z axes of the segment frame with respect to the X , Y , and Z axes of the space frame at time t .

Equation 2 presents the calculation of the segment angles in the frontal plane, $\theta_{YZ}(t)$, transverse plane, $\theta_{ZX}(t)$, and sagittal plane, $\theta_{XY}(t)$. The angular velocity was calculated through the Poisson equation and a five-point smoothing technique in each plane seen in Equation 3 (Zatsiorsky, 1998). The angular acceleration was then calculated by differentiating the angular velocity with a five-point smoothing technique (Amis et al., 1980). The linear velocity and linear acceleration were calculated by consecutively applying five-point smoothing techniques to the displacement of the center of mass of the segment (Winter, 1990).

$$\begin{aligned} \theta_{YZ}(t) &= \tan^{-1}(\cos_{Zy}(t)/\cos_{Yy}(t)) \\ \theta_{ZX}(t) &= \tan^{-1}(\cos_{Zx}(t)/\cos_{Xx}(t)) \\ \theta_{XY}(t) &= \tan^{-1}(\cos_{Xy}(t)/\cos_{Yy}(t)) \end{aligned} \quad (2)$$

where $\theta_{YZ}(t)$, $\theta_{ZX}(t)$ and $\theta_{XY}(t)$ are the segment angles on the frontal, transverse, and sagittal planes.



$$\begin{aligned}
\omega_{YZ}(t) &= \frac{\cos_{Xx}(t+\Delta t) - \cos_{Xx}(t-\Delta t)}{2\Delta t} \cos_{Yx}(t) + \frac{\cos_{Xy}(t+\Delta t) - \cos_{Xy}(t-\Delta t)}{2\Delta t} \cos_{Yy}(t) + \frac{\cos_{Xz}(t+\Delta t) - \cos_{Xz}(t-\Delta t)}{2\Delta t} \cos_{Yz}(t) \\
\omega_{ZX}(t) &= \frac{\cos_{Xx}(t+\Delta t) - \cos_{Xx}(t-\Delta t)}{2\Delta t} \cos_{Zx}(t) + \frac{\cos_{Xy}(t+\Delta t) - \cos_{Xy}(t-\Delta t)}{2\Delta t} \cos_{Zy}(t) + \frac{\cos_{Xz}(t+\Delta t) - \cos_{Xz}(t-\Delta t)}{2\Delta t} \cos_{Zz}(t) \quad (3) \\
\omega_{XY}(t) &= \frac{\cos_{Yx}(t+\Delta t) - \cos_{Yx}(t-\Delta t)}{2\Delta t} \cos_{Zx}(t) + \frac{\cos_{Yy}(t+\Delta t) - \cos_{Yy}(t-\Delta t)}{2\Delta t} \cos_{Zy}(t) + \frac{\cos_{Yz}(t+\Delta t) - \cos_{Yz}(t-\Delta t)}{2\Delta t} \cos_{Zz}(t)
\end{aligned}$$

where $\omega_{YZ}(t)$, $\omega_{ZX}(t)$ and $\omega_{XY}(t)$ are the angular velocities on the frontal, transverse, and sagittal planes.

3. Method

3.1. Subjects

Four healthy male students participated in the study. Table 1 shows the anthropometric dimensions and self-chosen normal luggage-pulling speeds.

Table 1. Anthropometric data and self-chosen normal luggage-pulling speeds

Subject	Age (year)	Height (cm)	Weight (kg)	Speed (m/s)
1	31	172	67	1.34
2	32	182	78	1.34
3	34	169	68	1.43
4	30	179	70	0.89

3.2. Apparatus

A luggage testing prototype used in the study was built with a steel and aluminum frame. The dimension of the prototype was 56 cm × 26 cm × 46 cm (International Air Transport Association, 2001). A wooden handle and hard-rubber wheels were exchangeable based on the experimental conditions. A strip of carpet was wrapped around the wheels to simulate a carpeted floor.

In Fig. 2, the left picture shows the configuration of 100 cm handle, parallel handle, 0° pole, 8 cm wheels, 15 kg load, low center of mass, and non-carpeting. The right picture shows the configuration of 110 cm handle, rotated handle, 10° pole, 15 cm wheels, 23 kg load, middle center of mass, and carpeting. Handle height was measured from the floor. The low and middle centers of mass of luggage were 19 cm and 31.4 cm of luggage height from the floor, respectively.



Fig. 2. Luggage prototype.



Luggage-pulling tasks were carried out on a doublewide treadmill with a walking surface of 102 cm × 145 cm. Two camcorders (DCR-TRV 740, SONY) were positioned perpendicular to the sagittal and frontal planes at a distance of 4 m from the treadmill. A three-minute luggage-pulling motion was captured for each task and sampled at 25Hz with MovieStar 5 (Dazzle DV-Editor, SCM Microsystems). The coordinates of the markers were manually collected with Multimedia Video Task Analysis (Version 2.8, Wisconsin Alumni Research Foundation).

3.3. Procedure

After being given the informed consent form, the subject was informed of experimental methods. The experimenter attached markers to the landmarks of the body and luggage, and measured the thickness between anterior superior iliac spines and posterior superior iliac spines, length between heel and second toe, and widths of elbow, wrist, knee, ankle, and between right and left anterior superior iliac spines.

The subject practiced pulling the luggage with the right hand on the treadmill for five minutes at a self-chosen normal walking speed. The subject randomly performed thirty-two tasks in two days. Each task took three minutes and a five-minute break was allowed between tasks. Each task was videotaped for three minutes and subjective ratings were collected during the break by using the Borg's overall and five local ratings of perceived exertion (RPE) for the torso, arms, and legs (Borg, 1998).



3.4. Data collection

One stride pulling motion was extracted from the three minute videotaping for data analyses. After manually collecting the coordinates of the markers from the one stride video clip and converting them with respect to the space frame, second order Butterworth filters were applied twice forwardly and backwardly with the cutoff frequency of 5 Hz to reduce the noise and phase distortion of the coordinate data (Winter, 1982). Pick angle, peak linear acceleration, and peak angular acceleration for each segment of the human model were collected during the stride.

3.5. Experiment design

Two-level fractional factorial design with resolution IV was employed for experimental design. Table 2 shows 9 two-level independent variables. Discrimination between short and tall subjects was based on the 50-percentile US civilian male height of 175.3 cm (Chaffin et al., 1999). Table 3 shows 141 dependent variables. Peak angle, peak linear acceleration, and peak angular acceleration for every plane or axis were collected from each segment.



Table 2. Independent variables and levels

IV	Low level	High level
Handle height	100 cm	110 cm
Handle rotation	Parallel	Rotated
Pole angle	0°	10°
Wheel diameter	8 cm	15 cm
Load weight	15 kg	23 kg
Center of mass	Low	Middle
Carpeting	No	Yes
Trial day	First	Second
Subject height	Short	Tall

Table 3. Dependent variables

Methods	No	DV	Planes or Axes	Segments
Kinematics	45	Peak angles	<i>XY, YZ, ZX</i>	Head/trunk, pelvis, right and left upper arms, right and left forearms, right and left hands, right and left thighs, right and left shanks, right and left feet, luggage
	45	Peak linear accelerations	<i>X, Y, Z</i>	
	45	Peak angular accelerations	<i>XY, YZ, ZX</i>	
Subjective ratings	6	Borg's ratings of perceived exertion		Overall, torso, right and left arms, right and left legs

3.6. Statistical analysis

With the use of Wilks' criterion, separate multivariate analysis of variance (MANOVA) was performed on each group of the absolute values of peak angles, peak linear accelerations, peak angular accelerations, and subjective ratings. Univariate analyses of variance (ANOVA) were then applied in order to find the main effects of the significant independent variables found by MANOVA on an individual dependent variable.



4. Results

4.1. Peak angle

The MANOVA revealed that the combined peak angle was significantly affected by all independent variables except carpeting. Handle rotation and subject height were more associated with the combined peak angles according to partial η^2 . Table 4 presents the results.

Table 4. MANOVA of peak angles

IV	Wilks' Lambda	F(45, 74)	p	η^2
Handle height	0.105	14.06	0.000	0.895
Handle rotation	0.068	22.52	0.000	0.932
Pole angle	0.275	4.33	0.000	0.725
Wheel diameter	0.453	1.99	0.004	0.547
Load weight	0.168	8.15	0.000	0.832
Center of mass	0.324	3.42	0.000	0.676
Trial day	0.299	3.85	0.000	0.701
Subject height	0.026	60.53	0.000	0.974

Tables 5 shows the results of the ANOVA for the individual peak angle variables. Handle height affected luggage angles on the sagittal and transverse planes. Luggage was tilted more forward but less twisted with 110 cm handle. Handle rotation affected the right hand supination and deviation. The right hand was less supinated and less deviated with the rotated handle than with the parallel handle. Pole angle had an effect on luggage and right foot. Luggage was tilted less forward but more twisted with 10° pole. The right foot was also less inversed or eversed with 10° pole. The right arm and head/trunk angles on the sagittal and frontal planes were influenced by wheel diameter. 15 cm wheels increased the right arm abduction and right hand



supination, but decreased the flexion/extension of the head/trunk, right forearm, and right hand. 23 kg load increased head/trunk and right shank flexions and both shank twisting, but decreased head/trunk bending and twisting, left upper arm abduction, left hand flexion/extension, and pelvis twisting. Luggage was tilted more forward with the middle center of mass. It also increased head/trunk bending and hand deviation angles. Trial day influenced both thighs and right shank. The right thigh and right shank were more abducted and both thighs were more twisted on the second day. Subject height affected most body segment angles. The tall subject had smaller angles in most body parts than the short subject, except right upper arm, left upper arm, and left forearm abduction angles and a right forearm flexion angle.



Table 5. ANOVA of peak angles (unit: radian). *XY*, *YZ*, and *ZX* represent sagittal, frontal, and transverse planes, respectively.

IV	Segment	Plane	Low level		High level		F(1, 118)	p
			Mean	SD	Mean	SD		
Handle height	Luggage	<i>XY</i>	0.769	0.091	0.854	0.083	89.87	0.000
		<i>ZX</i>	0.268	0.145	0.206	0.135	9.70	0.002
Handle rotation	Right hand	<i>YZ</i>	0.180	0.074	0.147	0.061	8.03	0.005
		<i>ZX</i>	0.226	0.509	1.565	0.007	523.10	0.000
Pole angle	Luggage	<i>XY</i>	0.892	0.092	0.731	0.102	116.08	0.000
		<i>ZX</i>	0.167	0.092	0.307	0.102	49.18	0.000
Wheel diameter	Right foot	<i>YZ</i>	1.263	0.344	1.125	0.251	6.85	0.010
	Head/Trunk	<i>XY</i>	0.098	0.047	0.078	0.036	7.67	0.007
	Right upper arm	<i>YZ</i>	0.189	0.077	0.225	0.074	12.57	0.001
	Right forearm	<i>XY</i>	0.254	0.099	0.212	0.099	8.95	0.003
	Right hand	<i>YZ</i>	0.177	0.067	0.210	0.071	11.93	0.001
		<i>XY</i>	0.362	0.171	0.298	0.181	4.30	0.040
Load weight	Head/Trunk	<i>YZ</i>	0.151	0.059	0.176	0.077	4.99	0.027
		<i>XY</i>	0.078	0.035	0.099	0.047	8.67	0.004
		<i>YZ</i>	0.076	0.026	0.066	0.029	8.73	0.004
		<i>ZX</i>	0.214	0.044	0.190	0.051	9.39	0.003
	Left upper arm	<i>YZ</i>	0.290	0.097	0.349	0.085	17.81	0.000
	Left forearm	<i>XY</i>	0.918	0.127	0.866	0.121	5.66	0.019
	Left hand	<i>XY</i>	1.163	0.098	1.123	0.106	4.94	0.028
	Pelvis	<i>ZX</i>	0.189	0.062	0.173	0.039	4.84	0.030
	Right shank	<i>ZX</i>	0.631	0.074	0.684	0.106	11.45	0.001
	Left shank	<i>ZX</i>	0.700	0.065	0.732	0.075	8.26	0.005
Center of mass	Head/Trunk	<i>YZ</i>	0.066	0.024	0.076	0.030	8.73	0.004
	Right hand	<i>ZX</i>	0.803	0.771	0.988	0.747	9.97	0.002
	Luggage	<i>XY</i>	0.802	0.104	0.821	0.089	4.46	0.037
	Right thigh	<i>YZ</i>	0.151	0.041	0.163	0.026	4.31	0.040
Trial day		<i>ZX</i>	0.018	0.005	0.020	0.003	7.34	0.008
		<i>YZ</i>	0.191	0.065	0.232	0.060	18.13	0.000
	Left thigh	<i>ZX</i>	0.018	0.004	0.020	0.002	4.57	0.035
	Right upper arm	<i>YZ</i>	0.161	0.057	0.253	0.067	81.73	0.000
Subject height		<i>ZX</i>	1.216	0.251	0.818	0.392	48.06	0.000
		<i>XY</i>	0.185	0.078	0.281	0.099	45.25	0.000
	Right forearm	<i>XY</i>	0.881	0.068	0.742	0.066	239.81	0.000
	Luggage	<i>ZX</i>	0.281	0.150	0.193	0.121	19.63	0.000
	Left upper arm	<i>XY</i>	0.693	0.074	0.600	0.133	23.54	0.000
		<i>YZ</i>	0.272	0.064	0.367	0.099	45.47	0.000
		<i>ZX</i>	1.432	0.074	1.354	0.204	8.17	0.005
		<i>YZ</i>	0.422	0.136	0.512	0.313	4.35	0.039
	Left forearm	<i>YZ</i>	0.422	0.136	0.512	0.313	4.35	0.039
	Pelvis	<i>XY</i>	0.650	0.194	0.444	0.184	36.43	0.000
	Right shank	<i>ZX</i>	0.212	0.052	0.150	0.030	71.12	0.000
		<i>XY</i>	0.974	0.034	0.873	0.138	31.10	0.000
		<i>YZ</i>	0.242	0.057	0.181	0.059	41.20	0.000
		<i>ZX</i>	0.688	0.045	0.628	0.120	14.77	0.000
	Left shank	<i>XY</i>	1.028	0.029	0.936	0.109	40.55	0.000
		<i>YZ</i>	0.216	0.047	0.161	0.083	21.22	0.000
		<i>ZX</i>	0.749	0.048	0.683	0.076	36.22	0.000



4.2. Peak linear acceleration

The MANOVA on the combined peak linear acceleration identified that handle height, handle rotation, wheel diameter, load weight, center of mass, trial day, and subject height were statistically significant. Table 6 shows the results. Subject height was most associated among those significant variables.

Table 6. MANOVA of peak linear accelerations

IV	Wilks' Lambda	F(45, 74)	p	η^2
Handle height	0.431	2.17	0.002	0.569
Handle rotation	0.471	1.85	0.009	0.529
Wheel diameter	0.512	1.57	0.043	0.488
Load weight	0.475	1.82	0.011	0.525
Center of mass	0.283	4.17	0.000	0.717
Trial day	0.446	2.04	0.003	0.554
Subject height	0.054	28.72	0.000	0.946



Table 7 shows the results of the ANOVA for the individual peak linear acceleration variables. The right shank and right foot were less accelerated along the cranial axis with 110 cm handle than with 100 cm handle. Handle rotation influenced the right forearm only whose linear acceleration decreased along the anterior axis with the rotated handle. 15 cm wheels reduced the linear accelerations of the right arm and luggage on the cranial axis. 23 kg load produced more acceleration in the left upper arm on the lateral axis than 15 kg load. It also produced more acceleration in the right foot and left shank, but less acceleration in the left thigh on the cranial axis. The middle center of mass of luggage increased the linear acceleration of the head/trunk, right arm, and luggage along the cranial axis, but decreased it in the right forearm and right hand along the lateral axis. Most leg segments were more accelerated along the cranial axis on the second day of trials than on the first day. Most segments were significantly affected by subject height. The tall subject had less linear acceleration along the anterior and cranial axes than the short subject.



Table 7. ANOVA of peak linear accelerations (unit: m/s^2). X, Y, and Z represent anterior, cranial, and right lateral axes, respectively.

IV	Segment	Axis	Low level		High level		F(1, 118)	p
			Mean	SD	Mean	SD		
Handle height	Right shank	Y	7.36	1.37	6.88	1.29	7.18	0.008
	Right foot	Y	12.58	2.21	11.82	2.00	4.98	0.028
Handle rotation	Right forearm	X	2.10	0.65	1.92	0.47	4.38	0.038
Wheel diameter	Right upper arm	Y	3.88	1.15	3.55	0.96	9.56	0.002
	Right forearm	Y	4.07	1.21	3.71	1.07	8.75	0.004
	Right hand	Y	4.42	1.20	4.04	1.09	8.03	0.005
	Luggage	Y	1.60	0.60	1.30	0.42	19.27	0.000
Load weight	Left upper arm	Z	2.09	0.40	2.31	0.54	7.26	0.008
	Right foot	Y	11.84	1.96	12.56	2.25	4.40	0.038
	Left thigh	Y	5.48	1.24	5.15	1.34	4.01	0.048
	Left shank	Y	6.77	1.23	7.35	1.42	6.25	0.014
Center of mass	Head/Trunk	Y	3.64	0.76	3.87	1.03	4.76	0.031
	Right upper arm	Y	3.44	0.91	3.99	1.15	26.13	0.000
	Right forearm	Y	3.57	1.01	4.21	1.21	27.54	0.000
		Z	1.79	0.42	1.58	0.33	8.99	0.003
	Right hand	Y	3.95	1.07	4.51	1.18	16.72	0.000
		Z	2.10	0.71	1.81	0.57	6.53	0.012
	Luggage	Y	1.16	0.39	1.73	0.52	71.30	0.000
Trial day	Right thigh	Y	5.29	1.06	5.66	1.12	4.46	0.037
	Right shank	Y	6.76	1.20	7.48	1.40	15.95	0.000
	Right foot	Y	11.81	2.00	12.59	2.21	5.24	0.024
	Left shank	Y	6.80	1.30	7.32	1.38	5.19	0.024
	Left foot	Y	10.74	1.75	11.85	2.91	7.40	0.008
Subject height	Head/Trunk	Y	4.40	0.52	3.11	0.75	144.60	0.000
	Right upper arm	X	2.50	0.59	1.79	0.51	51.65	0.000
		Y	4.49	0.67	2.93	0.79	209.78	0.000
	Right forearm	X	2.26	0.39	1.75	0.61	33.10	0.000
		Y	4.70	0.74	3.08	0.89	177.07	0.000
	Right hand	Y	5.01	0.76	3.44	0.93	135.06	0.000
	Left upper arm	X	6.41	1.44	5.38	0.90	22.78	0.000
		Y	3.31	0.67	2.29	0.52	103.42	0.000
	Left forearm	X	12.86	1.97	11.89	2.62	5.41	0.022
	Pelvis	X	3.76	0.38	2.88	0.72	71.48	0.000
		Y	4.39	0.65	3.20	0.75	98.88	0.000
	Right thigh	X	8.05	1.06	6.76	1.46	31.38	0.000
		Y	6.00	0.68	4.96	1.20	36.01	0.000
	Right shank	X	17.08	1.56	14.58	2.20	53.56	0.000
		Y	6.30	1.02	7.94	1.12	83.81	0.000
	Left thigh	X	9.16	1.37	6.89	1.61	72.94	0.000
Y		6.19	0.85	4.45	1.07	108.63	0.000	
Left shank	X	18.87	2.83	15.91	4.10	22.13	0.000	



4.3. Peak angular acceleration

The results of the MANOVA for the combined peak angular acceleration seen in Table 8 revealed that only handle height, handle rotation, and subject height were significant. Again, subject height was most associated with the combined variables.

Table 8. MANOVA of peak angular accelerations

IV	Wilks' Lambda	F(45, 74)	p	η^2
Handle height	0.501	1.64	0.030	0.499
Handle rotation	0.347	3.10	0.000	0.653
Subject height	0.086	17.46	0.000	0.914

As shown in Table 9, the 110 cm handle produced smaller angular acceleration for right forearm abduction and right shank flexion/extension, but produced greater acceleration in luggage twisting than the 100 cm handle. The rotated handle reduced the right upper arm-abduction angular acceleration. The tall subject showed smaller angular acceleration for most body parts than the short subject except for the right forearm and right thigh twisting.



Table 9. ANOVA of peak angular accelerations (unit: radian/second²). XY, YZ, and ZX represent sagittal, frontal, and transverse planes, respectively.

IV	Segment	Plane	Low level		High level		F(1, 118)	p
			Mean	SD	Mean	SD		
Handle height	Right forearm	YZ	5.60	2.08	4.98	1.35	4.47	0.037
	Luggage	ZX	15.17	18.46	24.77	29.24	5.69	0.019
	Right shank	XY	76.51	15.39	70.67	11.98	6.22	0.014
Handle rotation	Right upper arm	YZ	9.24	3.28	7.62	3.48	9.48	0.003
Subject height	Head/Trunk	XY	6.58	1.48	5.74	1.37	10.97	0.001
	Right upper arm	XY	5.25	1.87	2.97	2.06	45.12	0.000
YZ		9.85	3.61	7.01	2.66	29.41	0.000	
ZX		34.84	21.87	22.34	10.36	18.52	0.000	
	Right forearm	XY	7.77	2.41	6.25	2.45	14.09	0.000
		YZ	5.74	2.10	4.83	1.23	9.73	0.002
	Right hand	ZX	1.90	0.90	2.58	1.25	13.42	0.000
		XY	15.09	5.63	12.34	4.14	10.17	0.002
	Left upper arm	ZX	5.82	4.99	4.06	3.95	7.04	0.009
		XY	22.38	3.85	14.18	5.34	104.28	0.000
	Pelvis	YZ	37.60	8.90	28.74	10.47	25.99	0.000
		ZX	139.42	31.70	106.43	40.61	31.41	0.000
		XY	26.72	17.61	17.73	7.27	14.30	0.000
	Right thigh	YZ	52.29	50.17	21.80	12.68	21.33	0.000
		ZX	38.02	29.24	17.33	11.15	27.87	0.000
		YZ	10.93	1.80	8.90	1.82	42.25	0.000
	Right shank	ZX	17.17	3.18	13.86	4.54	22.54	0.000
		YZ	125.28	20.68	96.66	31.60	36.43	0.000
		ZX	71.87	11.16	62.39	13.15	19.21	0.000

4.4. Subjective ratings

Handle rotation, wheel diameter, load weight, center of mass, trial day, and subject height were significant for the combined subjective rating variable. Subject height and load weight were more associated with the perceived exertion. Table 10 presents the results.

Table 10. MANOVA of subjective ratings

IV	Wilks' Lambda	F(6, 113)	p	η^2
Handle rotation	0.892	2.27	0.042	0.108
Wheel diameter	0.715	7.51	0.000	0.285
Load weight	0.445	23.46	0.000	0.555
Center of mass	0.660	9.69	0.000	0.340
Subject height	0.166	17.46	0.000	0.914



Both overall RPE and right arm RPE were affected by all significant independent variables (Table 11). The subject felt more force requirement overall and in the right arm with the rotated handle than with the parallel handle. 15 cm wheels reduced perceived exertion in all body segments except the left arm. Both the 23 kg load and the middle center of mass increased perceived exertion in all body segments. The tall subject felt less force requirement than the short subject in most body segments.

Table 11. ANOVA of subjective ratings

IV	Segment	Low level		High level		F(1, 118)	p
		Mean	SD	Mean	SD		
Handle rotation	Overall	11.50	1.73	12.02	1.85	6.54	0.012
	Right arm	11.83	2.28	12.45	2.57	7.96	0.006
Wheel diameter	Overall	12.28	1.81	11.23	1.64	26.95	0.000
	Torso	10.78	1.66	10.02	1.52	12.35	0.001
	Right arm	12.77	2.49	11.52	2.23	31.82	0.000
	Right leg	10.77	2.16	10.08	1.76	8.06	0.005
	Left leg	10.56	2.10	10.00	1.77	4.63	0.034
Load weight	Overall	11.05	1.52	12.47	1.79	49.72	0.000
	Torso	9.77	1.28	11.03	1.70	33.73	0.000
	Right arm	10.97	2.17	13.31	2.11	111.87	0.000
	Left arm	7.89	1.49	8.92	2.24	9.84	0.002
	Right leg	9.91	1.68	10.94	2.15	18.13	0.000
Center of mass	Left leg	9.73	1.59	10.83	2.14	17.49	0.000
	Overall	11.08	1.57	12.44	1.77	45.44	0.000
	Torso	9.88	1.32	10.92	1.75	23.08	0.000
	Right arm	11.31	2.29	12.97	2.32	55.87	0.000
	Left arm	8.03	1.64	8.78	2.19	5.21	0.024
Subject height	Right leg	10.06	1.78	10.78	2.13	8.81	0.004
	Left leg	9.94	1.74	10.63	2.10	6.91	0.010
	Overall	12.56	1.23	10.95	1.92	63.70	0.000
	Torso	10.91	1.15	9.89	1.87	21.72	0.000
	Right arm	13.45	1.46	10.83	2.52	140.34	0.000
	Right leg	11.70	1.19	9.14	1.80	111.96	0.000
	Left leg	11.39	1.33	9.17	1.86	71.98	0.000



5. Discussion

5.1. Handle height

Handle height mainly affected the kinematics of the right forearm, right leg, and luggage. 110 cm handle caused luggage to tilt forward about 10% more than 100 cm handle. The reason for this is that luggage users did not attempt to adjust the height of the handle grip to reduce physical stresses while pulling luggage. According to Okunribido and Haslegrave (1999) and Kingma et al. (2003), two-wheeled manual vehicle users tended to maintain a certain height of handle grip regardless of handle length. Therefore, less tilted luggage with 100 cm handle came closer to users so as not to provide enough clearance between the right leg and luggage. With such less clearance, users may accelerate their right shank and right foot on the sagittal plane so as not to strike luggage by a heel.

Additionally, luggage was less twisted and less accelerated on the transverse plane with 110 cm handle. It may be the cause of smaller right forearm angular acceleration. This situation somewhat agreed with Okunribido and Haslegrave (1999) for manual vehicle stability. They found that operators felt greater stability with a long handle in the sustained phase of pushing a two-wheeled cylinder hand truck.

The fully extended handle of most commercial luggage is 100 cm in length. Based on the findings of this study, it may be recommendable to increase the maximum handle length to 110 cm with adjustability that allows users to determine their own convenient handle height. However, handle height change is not significant for force exertion felt by users.



5.2. *Handle rotation*

Handle rotation influenced right arm kinematics and overall and right arm perceived exertions. It is not surprising that handle rotation greatly affects right hand supination. The rotated handle caused the right hand to be neutral, whereas the parallel handle caused the right hand to be fully supinated. The rotated handle also resulted in less wrist deviation than the parallel handle. Though small differences, the rotated handle is of advantage to the right forearm and right upper arm in terms of the linear and angular accelerations. The right forearm was less accelerated in a forward/backward direction and the right upper arm was less twisted with the rotated handle. Das et al. (2002) and Wissenden and Evans (2000) studied the handle orientation with four-wheeled hospital meal cart and supermarket trolley, respectively. The handle that allows the arm to be more neutral increases arm comfort and vehicle stability as well.

Since the subject is not familiar with luggage with a rotated handle that is not currently available in the market, however, they might feel more perceived force requirement overall and in the right arm while pulling luggage having a rotated handle.

5.3. *Pole angle*

Pole angle was significant only for the angles of the luggage and right foot. The 10° pole tilted luggage forward about 18% less but twisted it about 83% more than the 0° pole. In terms of luggage-tilting angles, there is a distinct difference between the effects of handle height and pole angle. Luggage that was more tilted with 110 cm handle gives more clearance for the right leg by



placing itself further behind the subjects, while luggage that was less tilted with 10° pole gives more clearance by making itself erect without any position change. Similar to 110 cm handle reducing the accelerations of the right shank and right foot, the 10° pole may reduce the inversion/eversion angle of the right foot. However, more forward tilted luggage seems to be more stable because luggage with 0° pole had smaller twisting angles like that with 110 cm handle, but Okunribido and Haslegrave (1999) could not find the effect of pole angle on the stability of a two-wheeled cylinder trolley.

5.4. Wheel diameter

Wheel diameter had a consistent effect on the angles and linear accelerations of the right arm, head/trunk, and luggage. The movement of the significant segments mainly reduced on the sagittal plane such as forward/backward and upward/downward directions, but increased on the transverse plane especially in a sideways direction. In other words, the segments were less flexed/extended and less accelerated along the cranial axis, but more abducted with 15 cm wheels. According to the results of subjective ratings, the subjects needed less perceived force with 15 cm wheels. This may make them use more natural arm swing with 15 cm wheels, whereas they may concentrate more on pulling luggage forward with 8 cm wheels. While handling a manual vehicle, the stress reducing benefit of larger wheels has been well known (Hansson, 1968; Drury et al., 1975; David and Nicholson, 1985; Megaw and Gurung, 1996; Al-Eisawi et al., 1999). However, the extent of wheel diameter effect found in this study seems to be small because luggage was pulled on the smooth flat floor with a relatively light load.



5.5. *Load weight*

It is well known that the heavier the load, the more stressful the work (Banerjee et al., 1959; Datta et al., 1978, 1983; Jäger et al., 1984; Lawson et al., 1993; Resnick and Chaffin, 1995; Van der Beek et al., 2000). However, it was difficult to identify any consistent effect of load weight on kinematics. Only the angles and linear acceleration of most segments except the right arm were influenced by load weight. However, subjective ratings were consistent so that the subject needed more perceived force in all body parts with the 23 kg load, and the right arm was the most significant for force increment.

5.6. *Center of mass*

Only the angles and linear accelerations of the head/trunk, right arm, and luggage were affected by the center of mass of the luggage. The middle center of mass increased luggage-tilting angles due to increased flexion moment (Kingma et al., 2003). It also increased head/trunk bending and right hand deviation. Similar to the effect of wheel diameter regarding subjective ratings, the subject may pay more attention to pulling luggage forward with more force exertion rather than using a sideways arm swing so that the linear accelerations of the head/trunk, right arm, and luggage were reduced along the lateral direction when pulling luggage with middle center of mass.



5.7. *Carpeting*

It is well known that a carpeted floor induces a greater physical load due to the increased rolling friction between wheels and the floor (Al-Eisawi et al, 1999). Lawson et al. (1993) observed that, in handling a hospital cart, a carpeted floor increased the force requirement by 70% more than a vinyl floor. In the similar situation, Drury et al. (1975) also found the force requirement on a carpeted floor to be twice larger than on a hard floor. When pushing and pulling a laden cart, Das et al. (2002) found that about 94% more force was required on a carpeted floor than on the tile floor. However, carpeting was not found to be significant in this study due to an inappropriate experimental preparation. This study intended to simulate the carpeted floor by wrapping the wheels with the strip of carpet. However, this condition caused the carpet to contact the walking belt of the treadmill instead of the wheels to contact the carpet (as the treadmill belts could not be carpeted and be expected to function normally).

5.8. *Trial day*

The second day of trial caused larger angles and linear accelerations in both legs. This may be due to a training effect because all the subjects had not had the experience of walking on the treadmill with luggage. They might walk with restricted motion on the first day of trial, but after becoming familiar with luggage-pulling tasks on the treadmill, they used larger and more natural leg motion on the second day of trial.



5.9. Subject height

Since subject height had the largest values of partial η^2 for all the dependent variables and affected all the body parts, it seems to be the most significant for a luggage-pulling task. However, it is not clear whether the subject height difference is the major cause of the difference in kinematics between short and tall subjects. Seen in Table 1, the subjects used their own self-chosen walking speeds to pull luggage, and the small subjects walked about 24% faster than the tall subjects. With a faster walking speed, the short subject used a larger range of motion in all body parts and concentrated more on the motion in the sagittal plane than the tall subject in order to keep up with the treadmill belt-rolling speed. Manual vehicle-handling speed has a strong relationship with physical workload (Drury et al., 1975; Lee et al., 1991, 1992; Resnick and Chaffin, 1995). The faster the handling speed, the greater the stress the users experienced. It also corresponds with the results of perceived force exertion found in this study. Therefore, further research that uses a constant walking speed for all subjects is needed to differentiate the effects of subject height and pulling speed on the physical load of luggage users.



6. Conclusions

As part of handling manual vehicles in a workplace, pulling luggage was simulated in the laboratory setting to find its effects on the health and safety of flight crews and travelers. The findings of this study are as follows.

- Overall, a luggage-pulling task seems to fit the light work category because the subjects felt only light force exertion in terms of Borg's RPE scales.
- However, the right arm was the most strenuously affected body part when pulling luggage.
- Subjective height associated with walking speed seems to be so important that flight crews and travelers may not rush with luggage and use a proper luggage handle length to reduce the physical stress of the right arm.
- A luggage with a long handle, a rotated handle, an angled pole, and larger wheels may be considered for selection and design purposes.

Finally, this study used only four subjects. It may not provide enough statistical power to distinguish the effect of each independent variable on the kinematics of the segments during luggage-pulling tasks, and may create difficulty in generalizing the findings. Employing more subjects is required through power analysis for further research on the validation of the kinematic model developed in the study. Even though the statistical power was low due to the low number of subjects, an important benefit of the findings was that there is further confirmation that manufacturers of products that must be physically handled by consumers, should strive to allow



their products' users to maintain neutral body postures to the extent possible. This will help to minimize physical stress and greater comfort in the use of the product.



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