G Ital Med Lav Erg 2020; 42:1, 55-59
ISSN 1592-7830

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A comparison of the energy costs with use of different types of manual wheelchair in disabled persons

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ABSTRACT. The energy cost of physical activity is a well-documented field of research both in non-disabled subjects and in subjects with physical disabilities, in particular spinal cord lesions. The aim of this study was, therefore, to investigate the energy cost and subjective fatigue in disabled persons who make daily use of a manual wheelchair by comparing three different types of wheelchair (standard, lightweight and ultra-light) in order to obtain indices useful for prescribing the most effective and appropriate wheelchair-aid for the individual patient. The study was carried out on 18 patients affected by paraplegia or paraparesis due to spinal cord injury at different levels. Result revealed a significant difference across the three types of wheelchair, with the energy expenditure to cover 100 m increasing from the ultra-light (lowest expenditure) to the lightweight to the standard type (highest expenditure). The differences observed in the average energy consumed to cover a distance of 100 meters with the three types of wheelchair confirm the hypothesis that it is the weight of the wheelchair chosen by the rehabilitation team together with the patient that constitutes the fundamental criterion in making such a prescription. Obviously, in making the final choice, other factors as well need to be taken into account, such as the person's age and anthropometric characteristics, the nature of the disability and prognosis, the achievable degree of autonomy, functional capacities, personal preferences, the type of use (domestic or external), accessibility, reliability and durability, esthetic features, eventual accessories available, etc.

Key words: *wheelchair, energy cost.*

RIASSUNTO. Il costo energetico delle attività fisiche è un ambito di ricerca storicamente ben studiato e documentato sia in soggetti normodotati, sia in soggetti con disabilità fisiche ed in particolare con mielolesione. Obiettivo del lavoro è stato quello di raccogliere parametri di costo energetico e di affaticamento soggettivo in disabili che utilizzano quotidianamente la carrozzina manuale mediante un test eseguito con tre diverse tipologie di carrozzina (standard, leggera e superleggera) allo scopo di fornire parametri utili per una prescrizione dell'ausilio-carrozzina il più possibile corretto, efficace ed appropriato. Lo studio è stato condotto su 18 pazienti paraplegici o paraparetici da esiti di lesione midollare a diversi livelli. I risultati mostrano una significativa differenza fra i tre tipi di carrozzina utilizzati con il valore del costo energetico per percorrere 100 metri che aumenta progressivamente utilizzando la carrozzina superleggera, rispetto alla leggera, rispetto alla standard. I valori mediamente registrati nei consumi energetici spesi per percorrere 100 metri secondo noi avvalorano l'ipotesi che il peso della carrozzina, scelta dal team riabilitativo insieme con il soggetto, sia il pre-requisito fondamentale di tale

Introduction

The energy cost of physical activity is a well-documented field of research both in non-disabled subjects (1) and in subjects with physical disabilities, in particular spinal cord lesions (2, 3). In these patients, numerous studies have been carried out, with different aims and approaches, focused on the energy costs of their use of manual wheelchairs. In particular, the strains sustained and energy costs related to manual propulsion at different speeds (4-6) have been investigated, as well as the energy costs with use of lightweight versus ultra-light wheelchairs in persons with spina bifida (7). It has been shown, in patients with spinal cord lesions, that the speed and distance covered by ultra-light wheelchairs is greater, but the energy cost is lower only in paraplegic patients, not in those with tetraplegia (8). The energy cost of wheelchair propulsion has also been investigated in order to implement technical modifications or technological innovations to facilitate disabled individuals in pushing their wheelchair (9-12).

To optimize patients' use of the wheelchair, recent studies have focused on the influence of training and practice in acquiring a more efficient push technique (14-16). In addition to the physiological parameters, patients' subjective satisfaction in using their wheelchair has also been evaluated (17), and in this field the Borg Rating of Perceived Exertion (RPE) 6-20 scale (18) has often been used as an indicator, even though its correlation with the physiological responses to physical fatigue is debated (19).

However, few studies have focused on analyzing the energy costs of wheelchair propulsion in order to identify for prescription purposes the most appropriate type of wheelchair suitable for the clinical and functional conditions of patients with motor disability, in particular with spinal cord lesions (20). The aim of this study was, therefore, to investigate the energy cost and subjective fatigue in disabled persons who make daily use of a manual wheelchair by comparing three different types of wheelchair (standard, lightweight and ultra-light) in order to obtain indices useful for prescribing the most effective and appropriate wheelchair-aid for the individual patient.

prescrizione. Ovviamente nella scelta finale occorrerà tener conto caso per caso anche di molti altri elementi, quali l'età e le caratteristiche antropometriche della persona, la disabilità e la prognosi, il grado di autonomia raggiungibile, le capacità funzionali, le preferenze personali, il tipo di uso (domestico o esterno), l'accessibilità, l'affidabilità e la durata, le caratteristiche estetiche, gli eventuali optionals disponibili, ecc.

Parole chiave: carrozzina, costo energetico.

Materials and Methods

Subjects

This was a randomized, crossover trial in which each patient was randomly assigned to a sequence of three types of manually propelled wheelchairs, namely standard (**st**) (weight > 16 Kg), lightweight (**lg**) (13-16 Kg) and ultra-light (**ul**) (< 13 Kg). For each type of wheelchair, we utilized the same brand in all patients[1].

The study was carried out on 18 patients affected by paraplegia or paraparesis due to spinal cord injury at different levels. All patients were in a nearly stabilized clinical-functional condition and used their manual wheelchair on a daily basis. Patients with cardiac diseases, bronchopulmonary diseases, outcomes of other neurological diseases, and ongoing infections were excluded. The main characteristics of the study patients are summarized in Table I.

Experimental protocol

Patients were tested on each of the three different types of wheelchair on three consecutive days. For each test, they were instructed to propel the wheelchair, at whatever sustained speed they found comfortable, continuously for 6 minutes up and down a corridor, 50-m long and 2-m wide, of the Rehabilitation Institute. The corridor was exposed to daylight with a controlled temperature (23° C) and humidity (65%), and had an even, level floor. At the end of each test, subjects were asked to rate their perceived fatigue by means of the Borg RPE 6-20 scale (19). On the day of the first test, patients were requested to perform a handgrip test (instantaneous maximal grip strength) with the right-hand, consisting of three consecutive trials of which the mean value was taken. The primary outcome measure was the energy cost of propelling the wheelchair, measured by the Kcal needed to cover a distance of 100 m. Secondary outcome measures were the total distance covered in 6 min, total amount of Kcal needed, and the subjective perceived fatigue (Borg Scale).

Table I. ***Baseline characteristics and clinical data of study patients***

Patient	Sex	Age (years)	Weight (Kg)	Height (cm)	Disease	Time from onset (months)	Level of lesion	ASIA
D.J	F	23	50	169	Trauma	5	D12	A
C.G	M	18	85	180	Trauma	6	D5	B
S.N	M	27	62	185	Trauma	41	D6-D7	A
M.M	M	45	75	175	Trauma	9	D9-D10	A
B.M	M	32	65	180	Trauma	61	D4-D5	A
B.S	M	25	75	180	Trauma	42	D4-D5	B
G.S	M	25	52	179	Trauma	6	D12-L1	A
F.E.	F	51	74	170	Mielite	9	D 8	B
D.G.	M	76	81	172	Spondylodiscitis	72	D 9-10	C
R.T.	M	17	45	150	Spina bifida	82	L 1	B
L.D.	M	75	78	175	Dural fistula	14	D 6	B
T.C.	F	37	66	173	Aortic Dissection	7	L 1	C
A.A.	M	45	90	180	Removal of meningioma	16	D 3	B
M.P.	F	37	80	170	Trauma	92	D9	A
M.G.	M	75	73	163	Infection	88	D9	A
M.C.	M	47	72	182	Trauma	35	D7	A
B.L.	M	38	60	170	Infection	85	D6	B
G.A.	M	35	72	170	Infection	95	D6	A
MEAN SCORE	**40.4 ±18.8**	**69.7 ±12.2**	**173.5 ±8.2**			**42.5 ±35.2**		**A = 9 (50%) B = 7 (39%) C = 9 (11%)**

[1] The following wheelchairs were used in the study:
Surace Squillo (weight 16.5 Kg)(**st**), Meyra Eurochair (weight 15 Kg)(**lg**), Progeo Excelle Vario (weight 12.6 Kg)(**ul**).

Instruments used

To measure the subject's energy expenditure during the wheelchair exercise, we used the Bodymedia Sensewear Armband monitoring system (21). This device, selected for its reliability and ease of use, is positioned on the upper third of the subject's arm and has been demonstrated to not disturb the propulsion movement of the wheelchair. Through dedicated sensors, in particular accelerometers, numerous parameters are acquired and stored which are then elaborated by the device's software to obtain the final measurement of energy expenditure. For performance of the handgrip test, the classic Jamar dynamometer was used. The mean value of three maximal strength trials (22) repeated at 1-min intervals one after the other was used in this study.

Statistical analysis

Descriptive statistics of the collected data are reported as mean ± SD for continuous variables and number (frequency) for categorical variables. We examined differences in outcome measures using repeated measures analysis of variance (ANOVA) with the type of wheelchair (standard, lightweight and ultra-light) as the repeated, within-subjects factor. Significant results were followed up by post-hoc analyses (Tukey's HSD criterion) to compare the different pairs of wheelchair types. The relationship between variables was assessed by the Pearson correlation coefficient. Values of $p < 0.05$ were considered as significant. All analyses were carried out using the SAS/STAT® 9.2 statistical package.

Results

The study group consisted of 18 patients. Their demographic and clinical characteristics are reported in Table I. Results for each patient on the 3 tests are presented in Table II.

Results of the primary and secondary outcome variables for the three types of wheelchair are reported in Table III, together with the p-value for results of repeated measures ANOVA (column 5). Results from post hoc comparisons are reported in the same Table, columns 6-8 and in Figure 1.

ANOVA revealed a significant difference across the three types of wheelchair in the primary outcome measure, with the energy expenditure to cover 100 m increasing from the ultra-light (lowest expenditure) to the lightweight to the standard type (highest expenditure). A similar trend was observed for the meters covered in 6 min and for the Borg scale (both $p<0.0001$), although the total energy expenditure did not differ between the different types of wheelchair ($p=0.6$).

Post-hoc analysis revealed that the energy expenditure to cover 100 m differed significantly only comparing the ultra-light vs. standard type ($p<0.001$) and lightweight vs. standard type ($p<0.001$). There was no significant difference between the ultra-light and lightweight type. In contrast, considering the distance covered in 6 min and the BORG scale, all pairwise comparisons were significant.

Table II. ***Results in each single patient for handgrip strength and on the three wheelchair tests***

Patient	Grip (Kg)	Meters st	Kcal st	Kcal/100m st	Borg st	Meters lg	Kcal lg	Kcal/100m lg	Borg lg	Meters ul	Kcal ul	Kcal/100m ul	Borg ul
D.J	27	408	51	12.5	17	480	50	10.4	15	756	51	6.8	11
C.G	28	480	88	18.5	18	456	65	14.2	15	600	69	11.5	8
S.N	24	560	73	13.1	19	576	64	11.1	13	640	65	10.1	11
M.M	20	432	60	13.9	15	524	57	10.8	12	514	56	10.9	10
B.M	35	460	47	10.3	18	588	52	8.9	14	684	46	6.7	8
B.S	37	540	55	10.1	16	612	56	9.2	17	730	56	7.7	11
G.S	41	488	45	9.2	17	622	50	8	17	772	54	7	13
F.E.	34	330	37	11.2	13	535	39	7.2	11	498	43	8.6	13
D.G.	23	237	37	15.6	16	287	36	12.5	11	245	36	14.6	13
R.T.	19	215	36	16.7	14	285	42	14.7	13	325	41	12.6	11
L.D.	26	417	43	10.3	13	464	42	9	12	563	40	7.1	12
T.C.	20	348	46	13.2	17	360	39	10.8	15	528	55	10.4	13
A.A.	24	380	63	16.5	13	400	44	11.1	11	440	39	9.0	8
M.P.	39	500	39	7.8	16	540	38	7.0	12	600	36	5.9	9
M.G.	29	360	50	13.8	15	360	33	9.2	13	380	40	10.6	9
M.C.	26	460	38	8.2	15	440	36	8.1	13	410	35	8.6	14
B.L.	18	100	14	13.9	20	240	41	17.0	16	260	33	12.6	12
G.A.	39	520	43	8.2	18	576	43	7.4	16	720	43	5.9	13

Table III. ***Results of the primary and secondary outcome variables for the three types of wheelchair***

Variable	Standard	Lightweight	Ultra-light	p value	p lg vs st	p ul vs st	p ul vs lg
Energy cost to cover 100 m (Kcal)	12.4 ± 3.2	10.4 ± 2.8	9.3 ± 2.5	**<0.0001**	**<0.001**	**<0.001**	NS
Distance covered (m)	402 ± 122	464 ± 119	537 ± 167	**<0.0001**	**<0.01**	**<0.001**	**<0.01**
Kcal expenditure (in the test)	48.0 ± 16.2	45.9 ± 9.7	46.6 ± 10.6	0.60	NS	NS	NS
Borg Scale at end of test	16.1 ± 2.1	13.7 ± 2.0	11.1 ± 2.0	**<0.0001**	**<0.001**	**<0.001**	**<0.001**

A significant association was observed between handgrip strength and the energy expenditure to cover 100 m (negative linear relationship) for all types of wheelchair [r=-0.75 (Figure 2), r=-0.74 and r=-0.68 for ultra-light, lightweight and standard respectively, p<0.005 for all] and between handgrip strength and distance (positive linear relationship) for all types of wheelchair [r=0,68 (figure 3), r=0,76 and r=0.63 for ultra-light, lightweight and standard respectively, p<0.005 for all].

Discussion

In all tests carried out with the different types of wheelchair, subjects expended a similar overall amount of energy, i.e. the differences were non significant (see Kcal expenditure in Table III). A preliminary analysis of this finding, first of all, confirms the validity of our study protocol in that it demonstrates the homogeneity of the patient sample and tests performed. Hence, it supports our notion that the differences in energy costs are essentially due to the type of wheelchair used.

The differences observed in the average energy consumed to cover a distance of 100 meters with the three types of wheelchair (Table III) confirm the hypothesis that it is the weight of the wheelchair chosen by the rehabilitation team together with the patient that constitutes the fundamental criterion in making such a prescription. Obviously, in making the final choice, other factors as well need to be taken into account, such as the person's age and anthropometric characteristics, the nature of the disability and prognosis, the achievable degree of autonomy, functional capacities, personal preferences, the type of use (domestic or external), accessibility, reliability and durability, esthetic features, eventual accessories available, etc.

We found in 5 subjects that the energy expenditure to cover 100 meters was higher with the lightweight wheelchair than with the ultra-light one. Indeed, in one individual, it was higher with the lightweight than with

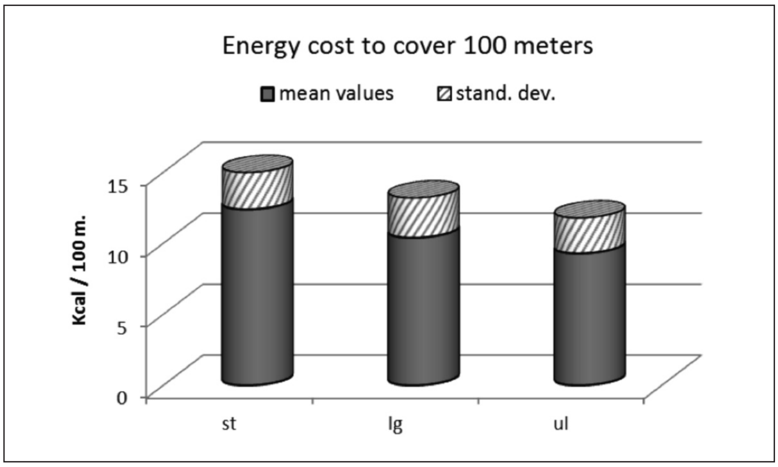

Figure 1. ***Energy cost to cover 100 meters with the different types of wheelchair (mean values for the 18 patients) (st = standard wheelchair, lg = lightweight wheelchair, ul = ultra-light wheelchair)***

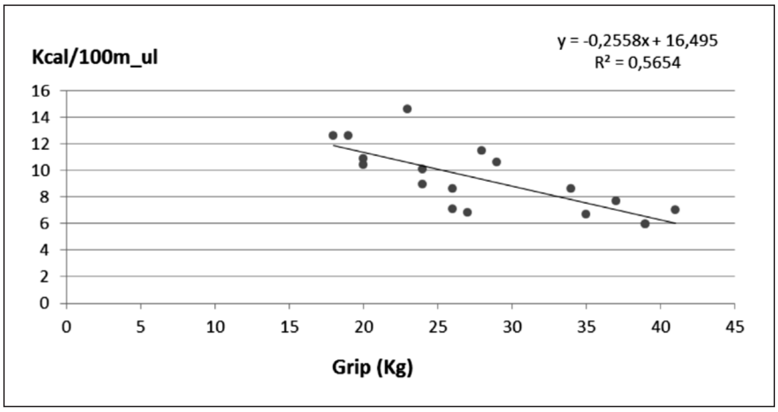

Figure 2. ***Correlation between handgrip strength and energy expenditure (with the ultra-light wheelchair)***

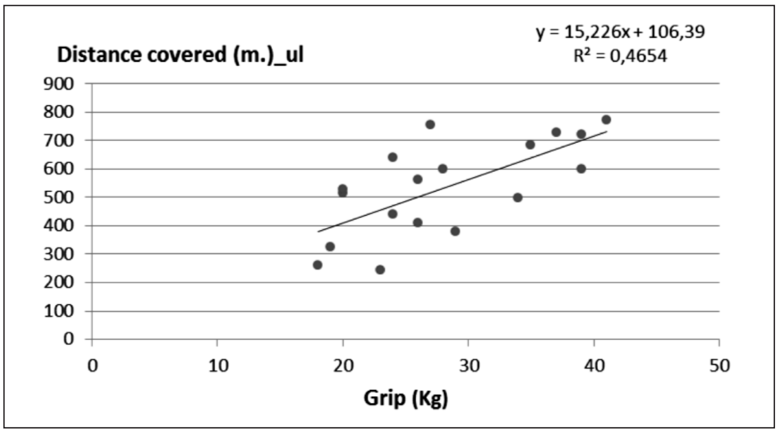

Figure 3. ***Correlation between handgrip strength and distance covered (with the ultra-light wheelchair)***

the standard wheelchair. A possible explanation for this is that, even if the weight of the wheelchair was the most important factor in determining the difference in energy consumption, other elements, nevertheless, can play a significant role at individual level and need to be optimized on a case-by-case basis, such as the wheelchair's adaptation to the person's build and seating position, the size of the seat, and hence the degree of abduction of the shoulders necessary for propelling the wheelchair, etc.

Significant differences were observed in the fatigue perceived by subjects at the end of the test (Borg Scale in Table III) in relation to the different types of wheelchair. We therefore maintain that this subjective element may be a useful factor to consider when choosing and prescribing the most appropriate wheelchair.

Finally, the significant correlation between handgrip strength and the performance with the ultra-light wheelchair, both in terms of lower energy expenditure and greater distance covered in the test (Figs. 2 and 3), highlights the importance of motor rehabilitation in these individuals, one of the key goals of which is to achieve the maximum improvement possible in developing and maintaining residual motor skills after spinal cord injury, i.e. physical strength and exercise tolerance, especially in the upper limbs (here exemplified by handgrip strength). This can facilitate patients in pushing their wheelchair, and make their wheelchair use much more effective and efficient. This, combined with the prescription of wheelchair that is most appropriate for the individual patient, will enhance the quality of life of disabled patients.

Conclusions

The use of the ultra-light wheelchair proved to be more effective and efficient in terms of both the objective and subjective measurements than that of the standard wheelchair and slightly better than use of the lightweight wheelchair. However, this performance advantage must be weighed against the costs of the different wheelchairs tested, which increase progressively in proportion to their efficiency, being higher for the lightweight wheelchair with respect to the standard type, and higher still for the ultra-light one.

It is therefore the task of the rehabilitation team and, above all, of the physiatrist and occupational therapist together with the patient, to assess all the information - clinical, functional, personal and environmental - pertinent for making an appropriate and effective prescription. For instance, in younger patients who are perhaps still actively engaged in a work context and/or with significantly reduced residual capacity, there would be a clear indication for the lightweight and especially the ultra-light wheelchairs as the first choice in such an assessment, on condition that the higher costs for these can be sustained by the public health services.

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