PHYSICAL ACTIVITY IN INDIVIDUALS WITH SPINAL CORD INJURY: EXERCISE AND TECHNOLOGIES FOR HEALTH PROMOTION

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In addition, ethical approval from the Human Research Ethics Committee of the University of Sydney and Medical Ethics Committee of the University of Malaya Medical Centre were granted for the studies presented in this thesis. Participants were required to read a participant information document and informed consent was gained prior to data collection.

Nazirah Hasnan

8th January 2014

Supervisor Statement

As supervisors of Nazirah Hasnan PhD studies, we certify her thesis “Physical Activity in Individuals with Spinal Cord Injury: Exercise and Technologies for Health Promotion” to be suitable for examination.

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Abstract

Spinal cord injury (SCI) adversely affects the physiological functions of most organ systems resulting in restrictions in performance of daily activities and social participation. Depending on the level of injury, SCI individuals can be amongst the most physically deconditioned of individuals with a disability. SCI renders profound effects on fitness, exercise capacities and health. There is increased risk of developing secondary health conditions such as cardiovascular disease and diabetes in chronic SCI survivors.

There is good evidence that exercise is effective for improving physical fitness and general health in the SCI population. Leg exercise is usually restricted because of paralysis after SCI and upper body exercise is not as beneficial as lower body exercise due to the relatively small muscle mass in the arms. Technological advancements have allowed functional electrical stimulation (FES) muscle contractions to enable exercise for the paralysed lower limbs of persons with SCI. Other technologies including virtual reality (VR) approaches have also begun to be deployed as exercise and rehabilitation strategies in recent years.

This thesis comprised of three studies, which examined exercise outcomes involving the use of assistive technologies (FES and VR) for exercise testing and training in persons with SCI.

The acute physiological response of FES-assisted cycling exercise was first assessed comparing the different exercise modalities that were available for people with SCI. These

were arm crank ergometry (ACE), FES–leg cycle ergometry (FES-LCE), ACE+FES-LCE and an integrated arm and FES-leg tricycle. It was found that combined arm and leg (hybrid) FES cycling exercise could develop higher oxygen uptake and cardiovascular demand compared to ACE or FES-LCE alone. Hybrid FES cycling evoked up to 148% higher oxygen uptake, 49% greater cardiac output and 47% higher heart rate than FES-LCE during steady-state exercise thereby concluding that FES-LCE by itself was insufficient to promote aerobic fitness and training benefit in people with SCI.

Based on the findings of the first experiment, the acute physiological and psychological responses to hybrid FES cycling were then further assessed in different exercise environment i.e. natural outdoor and simulated VR-enhanced indoor environment. With only 5% and 1% difference in the cardiorespiratory and perceptual-psychological responses respectively between the two modes, it was concluded that indoor and outdoor modes have similar exercise “dose-potency” and self-perceived effort.

Following these experiments on acute responses, a final study which examined the fitness, carbohydrate and lipid metabolisms and psychological outcomes following a 6-week high intensity interval training employing hybrid FES cycling training was carried out. The study demonstrated greater aerobic fitness by 16% and increased muscle mass by 6%. The 6-week training resulted in 60-80% improvement in negative mood states and up to 76% increase in post-exercise positive feeling states. However there was a lack of change in their lipid profile and glucose metabolism.

The importance of incorporating regular physical activity and exercise into the lifestyle of people with SCI is evident. The studies conducted herein identified the best exercise modality; propose strategies for enhancement of exercise participation and highlight the benefits of exercise in this population.

Abstrak

Kecederaan saraf tunjang menyebabkan terjejasnya kebanyakan fungsi fisiologi sistem organ badan. Pesakit-pesakit ini mengalami kekurang-upayaan dalam melaksanakan aktiviti harian dan penyertaan sosial. Bergantung kepada tahap kecederaan, mereka yang mengalami kecederaan saraf tunjang adalah antara yang mengalami ketidakupayaan dan dekondisi fizikal yang paling teruk. Kecederaan saraf tunjang menyebabkan kesan yang mendalam terhadap kecergasan, kapasiti senaman dan kesihatan. Terdapat juga peningkatan risiko untuk berlakunya komplikasi perubatan sekunder seperti penyakit jantung dan kencing manis.

Terdapat bukti bahawa senaman adalah berkesan untuk meningkatkan kecergasan fizikal dan kesihatan umum pesakit kecederaan saraf tunjang. Senaman menggunakan kaki adalah terhad kerana kelumpuhan selepas kecederaan saraf tunjang. Senaman melibatkan anggota atas badan tidak begitu bermanfaat seperti senaman menggunakan anggota bawah badan kerana jisim otot yang agak kecil pada lengan. Kemajuan teknologi terkini membolehkan “functional electrical stimulation” (FES), suatu teknik rangsangan saraf dan otot dengan menggunakan elektrik untuk membolehkan senaman menggunakan kaki bagi golongan ini. Pendekatan teknologi lain termasuk teknologi realiti maya “virtual reality” (VR) telah mula digunakan sebagai strategi senaman dan pemulihan dalam tahun-tahun kebelakangan ini.

Tesis ini terdiri daripada tiga kajian yang melihat respon semasa menjalani aktiviti senaman yang melibatkan penggunaan teknologi dalam menyokong ujian senaman dan latihan bagi orang yang mengalami kecederaan saraf tunjang.

Kajian pertama melibatkan penilaian respon akut semasa subjek-subjek menjalankan senaman FES-cycling, di mana perbandingan respon di antara modaliti senaman telah dijalankan. Modaliti tersebut adalah “arm crank ergometer” (ACE), functional electrical stimulation-leg cycle ergometry” (FES-LCE), ACE+FES-LCE dan basikal roda tiga yang telah diintegrasikan dengan pedal lengan dan unit FES. Hasil kajian menunjukkan bahawa penggabungan senaman lengan dan kaki (hybrid FES cycling) dapat meningkatkan permintaan kardiovaskular dan pengambilan oksigen yang tinggi berbanding dengan ACE atau FES-LCE sahaja. Hybrid FES cycling menghasilkan sehingga 148% penggunaan oksigen, 49% keluaran jantung dan 47% degupan jantung yang lebih tinggi dari hanya menggunakan modaliti FES-LCE semasa menjalankan ‘steady-state exercise”. Dengan itu dapat dirumuskan bahawa senaman menggunakan modaliti FES-LCE sahaja adalah tidak mencukupi untuk mempromosikan kecergasan aerobik dan mendapat faedah senaman yang sewajarnya untuk golongan yang mengalami kecederaan saraf tunjang.

Berikutan hasil dari kajian yang pertama, kajian seterusnya melibatkan penilaian akut respon psikologi dan fisiologikal terhadap hybrid FES cycling semasa menjalankan senaman di persekitaran luar dan di persekitaran dalam yang menggunakan teknologi realiti maya. Dengan hanya perbezaan sebanyak 5% dan 1% pada respon kardiorespirasi dan persepsi psikologi masing-masing, dapat dirumuskan bahawa persekitaran dalam atau luar memberi kesan yang sama dari segi “dose-potency” dan usaha senaman.

Berikutan eksperimen yang melibatkan gerakbalas akut, kajian terakhir melibatkan penilaian pencapaian dari segi kecergasan, metabolism karbohidrat dan lipid serta psikologi selepas menjalani program “high-intensity interval training” menggunakan hybrid FES cycling selama 6 minggu. Kajian ini telah menunjukkan peningkatan kecergasan aerobik sebanyak 16% dan penambahan jisim otot sebanyak 6%. Latihan selama 6 minggu mengakibatkan penambahbaikan sebanyak 60-80% keadaan mood negatif dan sehingga 76% peningkatan perasaan positif selepas menjalani senaman. Walaubagaimanapun, terdapat tiada perubahan dalam profil lipid dan metabolisma glukosa.

Kepentingan menjadikan aktiviti fizikal secara berkala dan senaman sebagai gaya hidup orang-orang yang mengalami kecederaan saraf tunjang telah terbukti. Kajian-kajian yang telah dijalankan telah mengenalpasti modaliti senaman yang terbaik; mencadangkan strategi untuk meningkatkan penyertaan dalam senaman dan menonjolkan manfaat senaman pada golongan ini.

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Terminology

The following terms and their meanings were adopted and consistently used during this thesis:

Assistive technology

Referred to any item, piece of equipment, or product system, whether acquired commercially, modified or customized that is used to maintain, increase, or improve the functional capabilities of individuals with disabilities (United States Assistive Technology Act of 2004)(Pennsylvania, 2012).

Complete injury

This term was used when there was an absence of sensory and motor function in the lowest sacral segments (S4-S5) (i.e. no sacral sparing) (Kirshblum et al., 2011).

Electrical stimulation

Within the context of this manuscript, electrical simulation referred to the process of eliciting muscular contractions elicited via electrical impulses arising from skin surface electrodes placed over neuromuscular motor points of muscles. The electrical impulses then artificially stimulate muscular contractions via the motor nerves innervating the selected muscle groups.

Exercise

Referred to a series of physical activity, which is structured, planned and repetitive (Caspersen, Powell, & Christenson, 1985).

Functional Electrical Simulation

Functional electrical stimulation (FES) is the application of external electrical current to produce muscle contractions, by neuromuscular stimulator, thereby bypassing the central nervous system (Holsheimer, 1998).

Functional Electrical Simulation Leg Cycle Exercise (FES-LCE)

Functional electrical stimulation leg cycle exercise referred to involuntary movements of the gluteal, quadriceps and hamstring muscle groups whereby stimulus was sequenced during appropriate angle ranges of the cycle ergometer pedals. The endpoint of this stimulation sequence was the non-voluntary performance of a cycling motion.

Health promotion

Process of enabling people to increase control over the determinants of health and thereby to improve their health (World Health Organisation, 1986).

Hybrid

In this manuscript, the term ‘hybrid’ was used to describe concurrent arm and leg exercise, whereby leg exercise was evoked by functional electrical stimulation leg cycle exercise

Incomplete injury

This term was used when there was preservation of any sensory and/or motor function below the neurological level that included the lowest sacral segments S4-S5 (i.e. presence of “sacral sparing”). Sensory sacral sparing includes sensation preservation (intact or impaired) at the anal mucocutaneous junction (S4-S5 dermatome) on one or both sides for light touch or pin prick, or deep anal pressure (DAP). Motor sacral sparing included the presence of voluntary contraction of the external anal sphincter upon digital rectal examination (Kirshblum et al., 2011).

Mechanical efficiency

Mechanical efficiency is usually used for human motor efficiency in terms of power produced for oxygen consumed. Higher efficiency (economy) is associated with better results achieved in various activities and sport disciplines. The mechanical efficiency in chosen motoric actions ranged from 2% to 80% depending on the working limb, amount and duration of work, types of performed exercises (eccentric, concentric, mixed), types of sport discipline practiced, type of muscles fibres involved or the calculation methods (Jobson, Hopker, Korff, & Passfield, 2012).

Mechanical efficiency – Gross mechanical efficiency

Gross mechanical efficiency was defined as the ratio between external power output (PO) and energy expenditure (de Groot et al., 2005).

Mechanical efficiency – Net mechanical efficiency

Net efficiency considered only that portion of the energy expenditure, which contributed directly to external work. Therefore with net efficiency excludes resting energy expenditure .

Neurological level of injury (NLI)

Referred to the most caudal segment of the spinal cord with normal sensory and antigravity motor function on both sides of the body, provided that there is normal (intact) sensory and motor function rostrally. The segments at which sensory and motor testing show normal function is found often to on different sides on the body. Thus, up to four different segments may be identified in determining the neurological level, i.e., R(ight)-sensory, L(eft)-sensory, R-motor, L-motor. The single NLI refers to the most rostral of these levels (Kirshblum et al., 2011).

Paraplegia

Referred to impairment or loss of motor and/or sensory function in the thoracic, lumbar or sacral (but not cervical) segments of the spinal cord, secondary to damage of neural elements within the spinal canal. With paraplegia, arm functioning is spared, but, depending on the level of injury, the trunk, legs and pelvic organs may be involved. The term is used in referring to cauda equina and conus medullaris injuries, but not to lumbosacral plexus lesions or injury to peripheral nerves outside the neural canal (Kirshblum et al., 2011).

Physical activity (PA)

Referred to any bodily movement produced by skeletal muscles that results in a reasonable amount of energy expenditure (Caspersen et al., 1985).

Spinal Cord Injury (SCI)

Spinal cord injury is a trauma to the spinal cord resulting in a change, temporary or permanent, in its motor, sensory and autonomic function (American Spinal Injury Association, 2000).

Secondary health conditions

Secondary health conditions are causally related to a disabling condition (i.e., occurs as a result of the primary disabling condition, in this context; spinal cord injury) and can be pathology, impairment, a functional limitation, or an additional disability. These conditions can be either of a physical or a psychosocial nature (Wyatt & White, 2000).

Tetraplegia

Referred to impairment or loss of motor and/or sensory function in the cervical segments of the spinal cord due to damage of neural elements within the spinal canal. Tetraplegia typically results in impairment of function of all four extremities as well as the trunk and pelvic organs. It does not include brachial plexus lesions or injury to peripheral nerves outside the neural canal (Kirshblum et al., 2011).

Virtual reality

Referred to a range of computing technologies that present artificially generated sensory information in a form that people perceive as similar to real-world objects and events (Wilson, Foreman, & Stanton, 1997).

Abbreviations

ACE	Arm crank ergometer
ACSM	American College of Sports Medicine
AD-ACL	Activation-deactivation adjective checklist
ADL	Activities of daily living
AHA	American Heart Association
ANOVA	Analysis of variance
ASIA	American Spinal Injury Association
BMI	Body mass index
BWSTT	Body weight supported treadmill training
$(Ca\text{-}Cv)O_2$	Arterio-venous oxygen difference
CO_2	Carbon dioxide
CHD	Coronary heart disease
CVD	Cardiovascular disease
ECG	Electrocardiogram
EIFI	Exercise-induced feeling inventory
ES	Electrical stimulation
FES	Functional electrical stimulation
FES-LCE	Functional electrical stimulation–leg cycle ergometer
FRE	Framingham Risk Equation
GPS	Global positioning system
HD	High definition
HDL	High-density lipoprotein

HIIT	High-intensity interval training
HR	Heart rate
HRmax	Maximal heart rate
HRR	Heart rate reserve
ISNCSCI	International Standard for Neurological and Functional Classifications of Spinal Cord Injury
LDL	Low-density lipoprotein
LMN	Lower motor neuron
ME	Mechanical efficiency
ME_G	Gross mechanical efficiency
ME_N	Net mechanical efficiency
OGTT	Oral glucose tolerance test
PA	Physical activity
PO	Power output
Q	Cardiac output
QUEST	Quebec user evaluation of assistive technology
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion
SCI	Spinal cord injury
SCORE	Systematic Coronary Risk Evaluation
SD	Standard deviation
SE	Standard error
SV	Stroke volume
TG	Triglycerides

TM	Treadmill
TPR	Total peripheral resistance
UMN	Upper motor neuron
VCO2	Carbon dioxide production
VE	Expired ventilation
VO2	Oxygen uptake
VO2peak	Peak oxygen uptake
VR	Virtual reality
VRSQ	Virtual reality symptom questionnaire
W	Watt

Units of measure

b	beats
$b \cdot m^{-1}$	beats per metre
$b \cdot min^{-1}$	beats per m inute
cm	centimetre
d	day
$d \cdot wk^{-1}$	day per week
deg	degree
g	gram
$g \cdot s^{-1} \cdot count^{-1}$	gram per second per count
Hz	hertz
kg	kilogram
L	litre
$L \cdot min^{-1}$	litre per minute
m	metre
mA	milliampere
MET	metabolic equivalent
$MET \cdot min \cdot wk^{-1}$	metabolic equivalent per minute per week
min	minute
$min \cdot d^{-1}$	minute per day
$min \cdot wk^{-1}$	minute per week
mL	millilitre
$mL \cdot b^{-1}$	millimetre per beat

$mL \cdot kg^{-1} \cdot min^{-1}$	millilitre per kilogram per minute
$mL \cdot min^{-1}$	millilitre per minute
$ml \cdot 100min^{-1}$	millilitre per 100 minute
$m \cdot min^{-1}$	metre per minute
$mmol \cdot L^{-1}$	millimole per litre
ms	millisecond
μs	microsecond
$rev \cdot min^{-1}$	revolution per minute
s	second
W	Watt
wk	week
y	year

Publications and presentations

Peer-reviewed journal

Hasnan, Nazirah; Ektas, Nalan; Tanhoffer, Aldre I. P.; Tanhoffer, Ricardo; Fornusek, Che; Middleton, James; Husain, Ruby; Davis, Glen M. Exercise Responses during Functional Electrical Stimulation Cycling in Individuals with Spinal Cord Injury. Medicine & Science in Sports & Exercise, Vol. 45, No. 6, pp. 1131-1138.

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