JIDR Journal of Intellectual Disability Research
Published on behalf of mencap and in association with IASSID

989

Journal of Intellectual Disability Research doi: 10.1111/jir.12883

VOLUME 65 PART 11 pp 989–997 NOVEMBER 2021

Association between physical fitness, body mass index and intelligence quotient in individuals with intellectual disabilities

R. Cabeza-Ruiz,[1] **M. E. Trigo-Sánchez,**[2] **M. Rodríguez-Servián**[3] **& P. T. Gómez-Píriz**[1]

1 *Department of Human Mobility and Sport Performance, Faculty of Education, University of Seville, Seville, Spain*
2 *Department of Experimental Psychology, Faculty of Psychology, University of Seville, Seville, Spain*
3 *University of Seville, Seville, Spain*

Abstract

Background Physical exercise seems to improve cognitive abilities at different physiological levels. Numerous studies have examined the relationship between physical fitness (PF), physical activity and cognition among populations without intellectual disabilities (ID), but very few have addressed this question with respect to people with ID. This study aimed to determine the correlation between intelligence quotient (IQ) and factors related to PF in healthy adults with ID.
Methods A multicentre cross-sectional study was conducted in 91 individuals with ID. All participants were assessed with the K-BIT tests and the following test items from the SAMU DIS-FIT Battery: body mass index, handgrip strength (HGS), leg strength, dynamic balance and physical endurance.
Results Significant differences between men and women were tested by multiple regression. IQ was found to be statistically related to HGS and leg strength, with a medium effect size. Statistical relationships were also found between sex and physical endurance, with a medium effect size, and HGS, with a large effect size.
Conclusions The study results highlight relationships between the variables of muscular strength and the participants' IQ. Further studies with experimental designs are needed to enhance the understanding of the relationships between PF and cognition in persons with ID.

Keywords Body composition, Cognition, Intellectual disability, Muscle strength, Physical fitness

Correspondence: M. Rodríguez-Servián, University of Seville, Seville, Spain. Tel: +34695110127 (e-mail: servian95@gmail.com).

Introduction

Intelligence can be defined as a set of cognitive skills with which a person is able to understand, confront and resolve situations of greater or lesser complexity. These skills include attentiveness, reasoning ability, memory, planning and problem solving (Sharma *et al.* 2019). Although it is not the only way to assess cognitive ability, intelligence is generally measured in terms of intellectual quotient (IQ), via instruments that quantify levels of performance in cognitive tests. Despite the controversy generated by the use of tests of general intelligence (Kovacs and Conway 2019), this evaluation is useful in many areas of research.

According to the American Association of Intellectual and Developmental Disabilities

(AAIDD), people with intellectual disability (ID) typically present a cognitive deficit that limits their abilities to fully interact with the context in which they live (Heller *et al.* 2004). As well as limitations in adaptive skills, people with ID have a lower IQ than those without ID. According to the Stanford–Binet (5th Ed., SB5) classification, an IQ of 90–109 represents an average level of intelligence, while IQ ≤ 75 is indicative of ID, which is classed as mild (IQ = 55–75), moderate (IQ = 40–54) and severe (IQ < 40) (Sattler 2008).

In addition to cognitive differences, people with ID perform lower in tests of physical fitness (PF) than people with no ID, regardless of age (Hilgenkamp *et al.* 2012). The American College of Sports Medicine (ACSM) defines PF as a set of abilities that people have or can acquire that enables them to perform everyday physical activities without undue fatigue (Riebe *et al.* 2018). Physical activity improves PF through the application of cardiorespiratory, muscular, bone, endocrine and psycho-neurological organic functions, among others. However, the components of PF most closely related to health parameters are cardiorespiratory fitness, muscular strength, flexibility and body composition (Ganley *et al.* 2011). Although the extent to which cognitive limitations affect PF is unknown, one factor that could have a major impact is the fact that many people with ID lead a sedentary lifestyle (Tyrer *et al.* 2019).

In recent years, studies have examined the relationships between PF, physical activity and cognitive ability in different populations. Improved cognitive performance, as a result of physical exercise, appears at different physiological levels in what has been termed the 'neurotrophic hypothesis'. In principle, physical exercise causes neurochemical transformations in the body, which in turn provoke molecular and cellular transformations (Level 1). These processes involve structural and functional changes in the brain (Level 2) that affect the execution of different cognitive abilities (Level 3) (Audiffren and André 2019; Herold *et al.* 2019). Numerous studies have used brain imaging procedures to analyse the relationships between PF, physical activity and the anatomy and physiology of different brain structures related to basic cognitive abilities. Some of these papers have considered the relationships between different programmes of physical activity and the results obtained in tasks involving working memory and brain activation, among healthy elderly people (Chen *et al.* 2019). According to the results obtained in these cognitive tests, the participants who practised sports activities, whether open ones such as basketball or tennis, or closed ones like swimming or jogging, did better than those whose physical activity was irregular and of low intensity. Similar research has been conducted in people with different neuropathologies such as multiple sclerosis (Motl *et al.* 2015), Alzheimer's disease (Pedroso *et al.* 2018) and Parkinson's disease (Fiorelli *et al.* 2019). In these studies, the participants with greater aerobic capacity presented relatively large brain structures related to cognitive abilities (such as the hippocampus or the thalamus) (Motl *et al.* 2015). Other studies have focused on the relationship between PF and cognitive ability via indirect tests. One systematic review sought to determine the relationship between PF and academic performance in young people (Santana *et al.* 2017). This review found that positive relationships in this respect mainly involved cardiorespiratory fitness. Correlations have also been found between aerobic aptitude and cognitive control in pre-adolescents without ID, among whom those who presented greater limitations in maintaining physical effort also had difficulty in adjusting cognitive control, in an increasingly demanding sequence of cognitive tasks (Westfall *et al.* 2017).

Many studies have used IQ as a cognitive variable in relation to PF. One such study, conducted with a population of adolescents, reported that a low IQ was significantly associated with an increased probability of developing obesity, in both male and female participants (Goldberg *et al.* 2014). Similar associations between physical activity and IQ have also been found in primary and secondary school students (El-Kholy and Elsayed 2015; Makharia *et al.* 2016). The relationship between IQ and PF seems to remain consistent even after controlling for demographic and socioeconomic factors (O'Callaghan *et al.* 2012).

Few studies have been carried out to investigate the relationship between physical exercise and cognition in people with ID, although some have considered the effect on verbal fluency of a treadmill task performed at different intensities by people with Down syndrome (Chen *et al.* 2014; Chen and Ringenbach 2019). The results obtained showed that moderate-intensity exercise, but not high-intensity exercise, facilitates semantic processing. However, in these studies, the sample was small, and so the results should be considered with caution. Another study reported that the adolescents with Down syndrome who scored best in tests of fine manual dexterity also obtained better results in tests of cognitive ability, such as cognitive planning or working memory (Chen *et al.* 2019). Finally, improvements in reaction time and decision-making processes have been observed in adolescents with ID after moderate cycling exercise, compared with a control group (Vogt *et al.* 2013).

In view of these considerations, and taking into account the need for further research to clarify the relationship between PF and cognition in people with ID, the main aim of the present study is to identify the relationships between muscular strength, cardiorespiratory fitness, dynamic balance, body composition and IQ in adults with ID.

Methods

Study participants

This multicentre cross-sectional study was conducted jointly by the Department of Human Movement and Sport Performance of the University of Seville and the SAMU Foundation (the SAMU DIS-FIT Study) (Cabeza-Ruiz 2020) from January to June 2018. The study population was composed of healthy individuals with ID who were recruited at 12 care centres placed in the province of Seville. The study was based on a correlational survey in which all measures were compiled simultaneously, both the predictor variables – IQ, sex and body composition – and all the physical performance variables.

The study participants were a convenient sample of 91 individuals with ID, of whom 26 were female and 65 were male. Their mean age was 38.90 years (*SD* = 9.72). All met the following inclusion criteria: (1) they had been diagnosed by the competent administration as presenting mild or moderate ID; (2) they were resident in a care institution; (3) they presented medical authorisation of aptitude for sports activities in order to avoid risks to their health during the physical tests; (4) when the study was performed, they were not regularly participating in sports activities or physical exercise programmes. The participants whose ID was related to a chromosomal syndrome, such as Down syndrome, were not statistically analysed, due to their special anatomical and physiological characteristics. The participants and their legal guardians received verbal and written information about the study aims and signed a participation consent form. The study was approved by the Ethical Committee of Biomedical Research of Andalusia (Spain) and followed the Helsinki guidelines for ethical research behaviour.

Measures

Physical fitness

Physical fitness was assessed at the participants' care centres, so that they should be in familiar surroundings. All evaluations were carried out in groups of 8–10 people, in the same time slot and by the same research team. All the researchers involved were trained in the correct performance of the tests and in dealing with the participants and the special characteristics they presented. Caregivers of subjects with disabilities were asked to be present so that the participants were accompanied by a reference family person during the evaluations. All physical tests were carried out in the same evaluation session. The duration of each session depended on the circumstances that arose. Due to the attention and memory characteristics of many people with ID, it was not possible to give the information collectively on how to carry out the tests; instead, each participant was informed of the protocol, individually, to ensure the feasibility of the tests.

Four variables of PF were selected as representative indicators of physical health: strength, cardiorespiratory capacity, body balance and body composition. The PF evaluation tests performed were those of the SAMU Disability Fitness Battery (SAMU DIS-FIT), which are known to obtain good psychometric results among people with ID, as follows: body composition (body mass index, BMI), handgrip strength, (HGS), 10-repetition sit-to-stand test (leg strength, LS), get-up-and-go test (dynamic balance, DB), and 6-min walk test (physical endurance, PE). At all times, the implementation protocol described in the SAMU-DISFIT Battery (Alcántara-Cordero *et al.* 2020; Cabeza-Ruiz 2020) was followed.

Regarding the order of application of the tests, the authors recommend that the BMI evaluations should be obtained first, and the PE evaluation conducted as the final element of the assessment. The order and duration of each test, for each participant, was as follows: 1st, BMI (5–8 min); 2nd, DB (2–3 min); 3rd, HGS (3 min); 4th, LS (5–7 min); and 5th, PE (10 min). No period of familiarisation was allowed prior to the tests in order to prevent the influence of a possible learning effect on the final results, but each participant was allowed a practice run before each test. Throughout the measurement process, the participants received positive, individualised feedback.

Intelligence quotient

All participants completed the Spanish version of the Kaufman Brief Intelligence Test (K-BIT; Kaufman 2000). The K-BIT is a standardised test that measures the general intelligence of individuals within a wide age range (4–90 years). It can be applied simply and quickly (15–30 min, approximately), making it an excellent tool for evaluating people with ID. The K-BIT has been used to assess people with ID, showing a good correlation with other intelligence tests as the Prudhoe Cognitive Function Test (PCFT; Tyrer *et al.* 2010) and the Revised Wechsler Intelligence Scale for Children-Revised (WISC-R; Webber and McGillivray 2011). The K-BIT is composed of two subtests: (2) vocabulary, a measure of verbal ability that requires oral responses; this section valuates verbal skills, language development, the formation of verbal concepts and information flow; (2) matrices, which measures non-verbal skills and the ability to solve new reasoning problems, presented via both figurative and abstract visual stimuli. The K-BIT provides a verbal intelligence index, a non-verbal intelligence index and an overall intelligence index or IQ that summarises the overall test performance. None of these tests requires a motor response. The K-BIT itself presents a simple means of interpreting the scores obtained in each subtest. All participants were evaluated by the psychological team at their respective care centres 2 weeks before the PF evaluations began.

Statistical analysis

Pearson's correlation indexes among the dependent variables (HGS, LS, DB and PE) were calculated. The significant correlations among these variables made it necessary to apply a Bonferroni adjustment in the subsequent analysis of each dependent variable, multiplying the observed probabilities by the number of dependent variables analysed (adjusted $P = P * 4$). Finally, multiple linear regression analysis of each dependent variable was performed as a function of IQ, adjusted for age, sex (dummy coding: 0 = female; 1 = male) and BMI. A level of statistical significance of 0.05 was assumed for all the tests, and ΔR^2 was taken as the effect size index, with standard reference values of 0.01, 0.06 and 0.14 as small, medium and large effect sizes, respectively, for a unique variable (Cohen 1988). The assumptions of normality, homoscedasticity and noncollinearity were checked, and no relevant problems were detected (lowest tolerance index = 0.97 and highest variance inflation factor (VIF) = 1.03). All statistical analyses were performed by SPSS, PASW Statistics 18. The *post hoc* power was calculated by G*Power for the regression analysis, $N = 91$, four predictors, $\alpha = 0.05$, and the medium effect size obtained was $1 - \beta = 0.96$. The statistical power was calculated *a posteriori*, given this sample size, and was higher than the acceptable minimum of 0.80 for the most complex analysis technique used.

Results

Participant characteristics

Fig. 1 shows the flow chart for participants' recruitment to the study. Of the 223 subjects initially eligible, 74 were excluded because they did not meet the inclusion criteria. A further 27 declined to participate and 21 were not included for other reasons (e.g. blindness). Of the remaining 101 people, seven did not complete all the tests in the PF assessment sessions and three were excluded from the data analysis due to errors in measurement or in test performance. Finally, thus, 91 participants were included and their performance analysed in the study. The drop-out rate was 9.9%.

Physical fitness and intelligence quotient

The descriptive analysis of all the predictor or dependent variables included in the study is shown in Table 1. As can be observed, significantly different results were obtained by men and women for IQ, PE and HGS, but not for age, BMI, LS or DB.

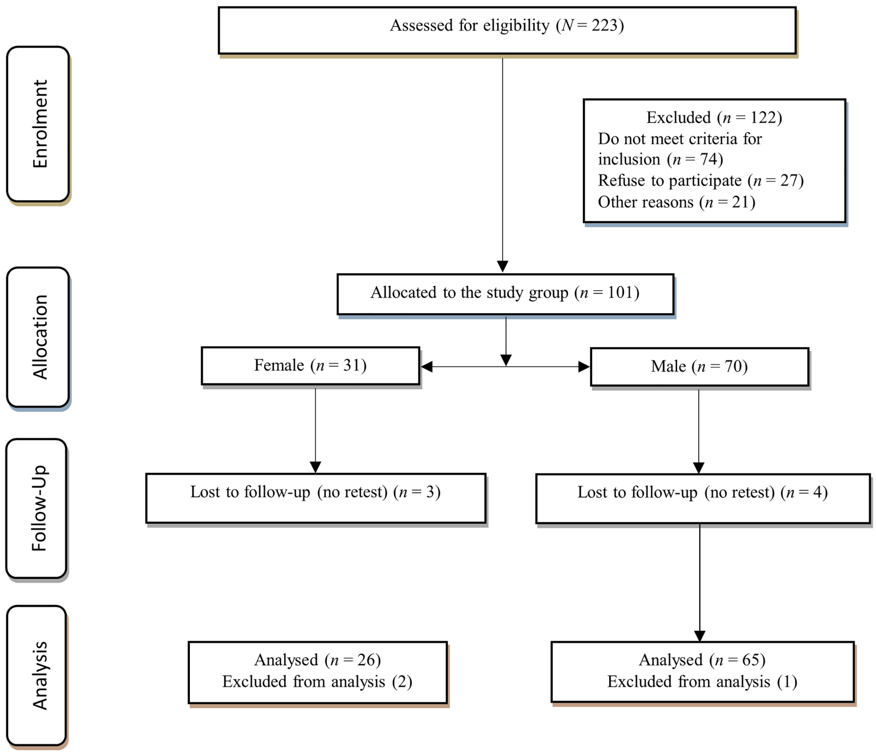

Figure 1. Flow chart of the sample recruitment process. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1 Descriptive statistics for sex and for quantitative variables by sex

Variable	Women (*n* = 26)	Men (*n* = 65)	All (*n* = 91)
Sex, %	28.6	71.4	100
Age, years	37.25 (9.29)	38.74 (9.76)	38.90 (9.72)
BMI, kg/m^2	30.05 (6.25)	28.76 (6.03)	28.91 (6.40)
IQ	54.08 (10.95)	56.05 (12.42)	55.47 (11.97)
PE, m	464.85 (74.66)	533.00 (81.32)	515.13 (81.29)
HGS, kg	22.26 (6.29)	31.98 (9.80)	29.02 (9.62)
LS, s	18.63 (7.05)	18.35 (5.62)	18.05 (5.91)
DB, s	4.58 (1.05)	4.17 (0.84)	4.29 (0.95)

Notes: All continuous data are presented as mean (*SD*).
Abbreviations: BMI, body mass index; DB, dynamic balance; HGS, handgrip strength; IQ, intelligence quotient; LS, leg strength; PE, physical endurance.

Significant differences between men and women were tested by a multiple regression analysis.

As shown in Table 2, after controlling for all other predictors, IQ was found to be statistically related to HGS and LS, with a medium effect size. Figs 2 and 3 show the partial regression slopes for each of these variables vs. IQ, revealing a positive relationship between HGS and IQ, and a negative one between LS (time elapsed) and IQ. Statistical relationships were also found between sex and PE, with a medium effect size, and HGS, with a large effect size. Finally, in the prediction of DB, BMI had a medium effect size but did not reach statistical significance.

Discussion

The main finding of the present study is that IQ is significantly related to the variables representing muscle strength, in the lower and upper body, in people with ID. Regarding the strength of the lower body, the IQ is inversely associated with LS because the sit-to-stand test is based on the time a person takes to perform the exercise. Thus, the higher the IQ, the faster the test execution. These results are in line with those obtained in previous studies, according to which cognitive performance benefits from training to improve muscle strength in people with dementia and

Table 2 Multiple linear regression analyses of each physical variable as a function of IQ, adjusted by age, sex and BMI

Fitness variables	B	*SE*	*t* (*df* = 76)	adj. *P*	ΔR^2
PE					
IQ	0.10	0.74	0.96	1.000	<0.01
Sex	0.35	19.41	3.35**	**0.005**	**0.12**
Age	−0.09	0.93	−0.85	1.000	<0.01
BMI	−0.16	1.47	−1.51	0.539	0.02
HGS					
IQ	0.35	0.08	3.72**	**0.001**	**0.12**
Sex	0.43	2.05	4.53**	**<0.001**	**0.18**
Age	−0.04	0.10	−0.42	1.000	<0.01
BMI	0.04	0.16	0.36	1.000	<0.01
LS					
IQ	−0.33	0.06	−3.10**	**0.010**	**0.11**
Sex	−0.01	1.43	−0.05	1.000	<0.01
Age	0.08	0.07	0.77	1.000	<0.01
BMI	−0.04	0.11	−0.35	1.000	<0.01
DB					
IQ	−0.16	0.01	−1.46	0.591	0.02
Sex	−0.18	0.21	−1.68	0.389	0.03
Age	0.11	0.01	1.05	1.000	0.01
BMI	0.26	0.02	2.44	0.068	**0.07**

*Adjusted $P < 0.05$.
**Adjusted $P < 0.01$.
Abbreviations: BMI, body mass index; DB, dynamic balance; HGS, handgrip strength; IQ, intelligence quotient; LS, leg strength; PE, physical endurance.
Notes: Significant relationships and medium or large effect size indexes are highlighted in bold.

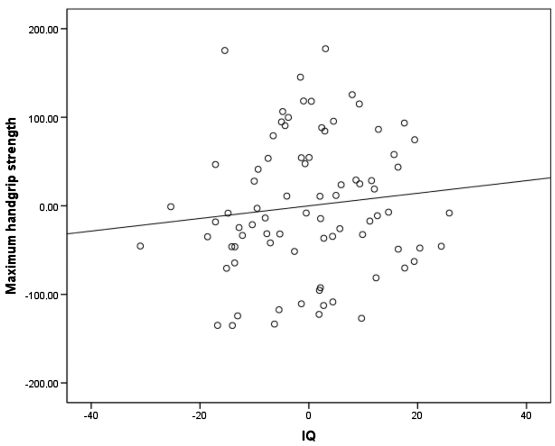

Figure 2. Partial regression graph for maximum handgrip strength vs. intelligence quotient (IQ).

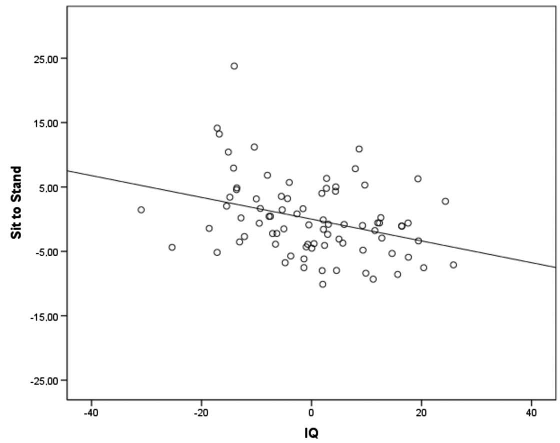

Figure 3. Partial regression graph for sit-to-stand vs. intelligence quotient (IQ).

Alzheimer's disease (Marston *et al.* 2019). Other studies have found significant relationships between lower limb muscle strength and positive results in standard cognitive tests, although these analyses were conducted of people without ID (Steves *et al.* 2016).

Regarding upper body strength, IQ was positively correlated with HGS (medium effect size). Previous studies have reported finding similar relationships between HGS and cognitive abilities in physically healthy people with some degree of mental disorder (Sternäng *et al.* 2016; Firth *et al.* 2018a, 2018b). The present research is especially significant in view of the very few similar studies conducted in people with ID.

Results show that IQ appears to be more closely related to the variables of strength than to PE or DB. Although various studies have investigated the relationship between aerobic fitness and cognition, focusing in particular on the effect of cardiorespiratory fitness (CRF) on the anatomical and/or functional state of the brain, in most cases the participants' muscular strength is not taken into account (Dupuy *et al.* 2015; Oberlin *et al.* 2016; Hwang *et al.* 2017; Opel *et al.* 2019; Park and Etnier 2019). Previous analyses do not clarify whether an increase in the participant's cognitive capacity is due to improved CRF or to the increased muscle strength derived from cardiovascular training, since both capacities interact and muscle strength is necessary to carry out any physical task without undue fatigue. In this respect, one study concluded that the strength of the lower extremities impacts on the results obtained in ergometer tests of maximum effort. In other words, the greater the muscle strength, the better the CRF test results in people with ID (Fernhall and Pitetti 2000). Further investigation is needed of the relationships between muscular strength, CRF and cognitive ability.

In addition to the above questions, the relationship between CRF and cognition seems to depend on the type of test selected to assess it and on the particular skills involved, such as running, walking or rowing (Kantomaa *et al.* 2013; Haapala *et al.* 2015). The fact that the present study detected no significant relationships between IQ and PE may be because the 6-min walk test is less demanding at the cognitive level than a laboratory ergometer test, in that walking is a mechanised, familiar skill. However, the circumstances are different with the SAMU-DISFIT reference battery strength tests.

Statistical analyses detected no relationship between DB and IQ, although previous studies have observed relations between the performance of older adults in coordination and cognitive functioning tests, concluding that different types of training (cardiovascular vs. motor fitness) produce improvements in different areas of the brain and in brain networks (Voelcker-Rehage *et al.* 2011). A study of primary school children, moreover, reported an association between motor fitness and reading comprehension (Uhrich and Swalm 2007). Although the latter study found no relationship between the DB results obtained and the participants' IQ, this may have been due to the type of test used. Get-up-and-go is a simple test in which the subject is not required to perform demanding skills and so differences obtained in the results may not be detectable by measures of statistical correlation. The use of physically more complex and change-sensitive tests might produce different outcomes.

Study limitations

On the one hand, the main limitation of the present study concerns intelligence assessment. We used the K-BIT instrument to assess the participants' IQ. However, many other instruments have been used in the context of IQ and PF, such as the Peabody Verbal IQ Test (O'Callaghan *et al.* 2012), or to relate IQ with physical activity and body composition, such as the Raven Test (El-Kholy and Elsayed 2015). In previous research, K-BIT has been used to assess IQ in people without ID (Hwang *et al.* 2017; Westfall *et al.* 2017) and with ID (Tyrer *et al.* 2010). In future studies of this type, it would be advisable to employ a commonly agreed measurement instrument, in order to enable direct comparisons between different studies. Similarly, using a common battery of tests to assess the PF of people with ID, as the SAMU-DISFIT Battery, would greatly facilitate our understanding of the links between PF and intelligence. On the other hand, although using a convenience sample limits the possibilities of statistical generalisation, the power calculations and the joint use of the significance and effect size indices attempt to guarantee the statistical conclusion validity.

Perspective for future research

Although the evidence reported is a good starting point, further study is needed to clarify three fundamental questions regarding the relationship between cognition and PF: (1) Does better PF result in improved cognitive performance? (2) Which elements of PF are more strongly associated with cognition? (3) From the above, what consequences would changes in PF have on the brain structures related to cognitive abilities and capacities, especially in people with ID? If these questions are satisfactorily resolved, physical activity programmes can be developed to improve the cognitive skills of people with ID. Consequently, experimental, longitudinal studies should be designed and implemented to determine causal relationships between these variables, and thus clarify the relationship between PF and cognitive ability in people with ID. Ultimately, therefore, we wish to answer the question: can learning abilities of people with ID be improved by physical conditioning?

Conclusions

This paper describes a study conducted to clarify the relationship between PF and IQ in people with ID. Among other findings, a significant association was observed between IQ and muscle strength, both in the lower and in the upper body. However, no such relationship was found with PE, DB or BMI. One of the main strengths of this study is that it is one of very few to examine the relationship between muscle strength, CRF, dynamic balance, body composition and IQ in adults with ID.

Acknowledgements

The research team would like to thank the participants in this study, their families and all the personnel at the respective care centres, especially those in the psychology departments, for their participation and collaboration in ensuring the correct performance of this study.

Source of Funding

This study was funded by the SAMU Foundation.

Conflict of interest

The authors have no conflicts of interest to declare.

Data availability statement

The data used in this study are reliable and have been analysed in accordance with international ethical considerations.

References

Alcántara-Cordero F. J., Gómez-Píriz P. T., Sánchez-López A. M. & Cabeza-Ruiz R. (2020) Feasibility and reliability of a physical fitness tests battery for adults with intellectual disabilities: the SAMU DIS-FIT battery. *Disability and Health Journal* **13**, 100886.

Audiffren M. & André N. (2019) The exercise–cognition relationship: a virtuous circle. *Journal of Sport and Health Science* **8**, 339–47.

Cabeza-Ruiz R. (2020) Considerations for the design of a physical fitness battery to assess adults with intellectual disabilities: preliminary reference values for the SAMU DIS-FIT study. *International Journal of Environmental Research and Public Health* **17**, 9280.

Chen C. C. J. J. & Ringenbach S. D. R. (2019) The effect of acute exercise on the performance of verbal fluency in adolescents and young adults with Down syndrome: a pilot study. *Journal of Intellectual Disability Research* **63**, 614–23.

Chen C. C. J. J., Ringenbach S. D. R., Albert A. & Semken K. (2014) Fine motor control is related to cognitive control in adolescents with Down syndrome. *International Journal of Disability, Development and Education* **61**, 6–15.

Chen F.-T., Chen Y.-P., Schneider S., Kao S.-C., Huang C.-M. & Chang Y.-K. (2019) Effects of exercise modes on neural processing of working memory in late middle-aged adults: an fMRI study. *Frontiers in Aging Neuroscience*, **11**.

Cohen J. (1988) *Statistical Power Analysis for the Behavioral Sciences*. Lawrence Erlbaum Associates, Hillsdale, NJ.

Dupuy O., Gauthier C. J., Fraser S. A., Desjardins-Crèpeau L., Desjardins M., Mekary S. *et al.* (2015) Higher levels of cardiovascular fitness are associated with better executive function and prefrontal oxygenation in younger and older women. *Frontiers in Human Neuroscience* **9**, 66.

El-Kholy T. & Elsayed E. (2015) Association of physical activity and health status with intelligence quotient of high school students in Jeddah. *Journal of Physical Therapy Science* **27**, 2039–43.

Fernhall B. & Pitetti K. H. (2000) Leg strength is related to endurance run performance in children and adolescents with mental retardation. *Pediatric Exercise Science* **12**, 324–33.

Fiorelli C. M., Ciolac E. G., Simieli L., Silva F. A., Fernandes B., Christofoletti G. *et al.* (2019) Differential acute effect of high-intensity interval or continuous moderate exercise on cognition in individuals with Parkinson's disease. *Journal of Physical Activity and Health* **16**, 157–64.

Firth J., Firth J. A., Stubbs B., Vancampfort D., Schuch F. B., Hallgren M. *et al.* (2018a) Association between muscular strength and cognition in people with major depression or bipolar disorder and healthy controls. *JAMA Psychiatry* **75**, 740–6.

Firth J., Stubbs B., Vancampfort D., Firth J. A., Large M., Rosenbaum S. *et al.* (2018b) Grip strength is associated with cognitive performance in schizophrenia and the general population: a UK Biobank study of 476 559 participants. *Schizophrenia Bulletin* **44**, 728–36.

Ganley K. J., Paterno M. V., Miles C., Stout J., Brawner L., Girolami G. *et al.* (2011) Health-related fitness in children and adolescents. *Pediatric Physical Therapy* **23**, 208–20.

Goldberg S., Werbeloff N., Fruchter E., Portuguese S., Davidson M. & Weiser M. (2014) IQ and obesity in adolescence: a population-based, cross-sectional study. *Pediatric Obesity* **9**, 419–26.

Haapala E. A., Lintu N., Väistö J., Robinson L. E., Viitasalo A., Lindi V. *et al.* (2015) Associations of physical performance and adiposity with cognition in children. *Medicine and Science in Sports and Exercise* **47**, 2166–74.

Heller T., Hsieh K. & Rimmer J. H. (2004) Attitudinal and psychosocial outcomes of a fitness and health education program on adults with Down syndrome. *American Journal on Mental Retardation* **109**, 175–85.

Herold F., Törpel A., Schega L. & Müller N. G. (2019) Functional and/or structural brain changes in response to resistance exercises and resistance training lead to cognitive improvements – a systematic review. *European Review of Aging and Physical Activity* **16**, 10.

Hilgenkamp T. I. M., van Wijck R. & Evenhuis H. M. (2012) Low physical fitness levels in older adults with ID:

results of the HA-ID study. *Research in Developmental Disabilities* **33**, 1048–58.

Hwang J., Castelli D. M. & Gonzalez-Lima F. (2017) The positive cognitive impact of aerobic fitness is associated with peripheral inflammatory and brain-derived neurotrophic biomarkers in young adults. *Physiology and Behavior* **179**, 75–89.

Kantomaa M. T., Stamatakis E., Kankaanpaa A., Kaakinen M., Rodriguez A., Taanila A. *et al.* (2013) Physical activity and obesity mediate the association between childhood motor function and adolescents' academic achievement. *Proceedings of the National Academy of Sciences* **110**, 1917–22.

Kaufman A. (2000) *Kaufman Brief Intelligence Test*. TEA, Madrid.

Kovacs K. & Conway A. R. A. (2019) A unified cognitive/differential approach to human intelligence: implications for IQ testing. *Journal of Applied Research in Memory and Cognition* **8**, 255–72.

Makharia A., Nagarajan A., Mishra A., Peddisetty S., Chahal D. & Singh Y. (2016) Effect of environmental factors on intelligence quotient of children. *Industrial Psychiatry Journal* **25**, 189–94.

Marston K. J., Brown B. M., Rainey-Smith S. R. & Peiffer J. J. (2019) Resistance exercise-induced responses in physiological factors linked with cognitive health. *Journal of Alzheimer's Disease* **68**, 39–64.

Motl R. W., Pilutti L. A., Hubbard E. A., Wetter N. C., Sosnoff J. J. & Sutton B. P. (2015) Cardiorespiratory fitness and its association with thalamic, hippocampal, and basal ganglia volumes in multiple sclerosis. *NeuroImage: Clinical* **7**, 661–6.

Oberlin L. E., Verstynen T. D., Burzynska A. Z., Voss M. W., Prakash R. S., Chaddock-Heyman L. *et al.* (2016) White matter microstructure mediates the relationship between cardiorespiratory fitness and spatial working memory in older adults. *NeuroImage* **131**, 91–101.

O'Callaghan F., O'Callaghan M., Williams G., Bor W. & Najman J. (2012) Physical activity and intelligence: a causal exploration. *Journal of Physical Activity and Health* **9**, 218–24.

Opel N., Martin S., Meinert S., Redlich R., Enneking V., Richter M. *et al.* (2019) White matter microstructure mediates the association between physical fitness and cognition in healthy, young adults. *Scientific Reports* **9**, 12885.

Park S. & Etnier J. L. (2019) Beneficial effects of acute exercise on executive function in adolescents. *Journal of Physical Activity and Health* **16**, 423–9.

Pedroso R. V., Cancela J. M., Ayán C., Stein A. M., Fuzaro G., Costa J. L. R. *et al.* (2018) Effects of physical exercise on the P300 of elderly with Alzheimer's disease. *Journal of Physical Activity and Health* **15**, 403–10.

Riebe D., Ehrman J. K., Liguori G., Magal M. & American College of Sports Medicine (2018) *ACSM's Guidelines for Exercise Testing and Prescription*, 10th edn. Wolters Kluwer, Philadelphia.

Santana C. C. A., Azevedo L. B., Cattuzzo M. T., Hill J. O., Andrade L. P. & Prado W. L. (2017) Physical fitness and academic performance in youth: a systematic review. *Scandinavian Journal of Medicine and Science in Sports* **27**, 579–603.

Sattler J. M. (2008) *Assessment of Children: Cognitive Foundations and Applications*. Sattler Publisher, La Mesa, CA, Jerome M.

Sharma V., Kaur M., Gupta S. & Kapoor R. (2019) Relationship of emotional intelligence, intelligence quotient, and autonomic reactivity tests in undergraduate medical students. *Medical Science Educator* **29**, 673–81.

Sternäng O., Reynolds C. A., Finkel D., Ernsth-Bravell M., Pedersen N. L. & Dahl Aslan A. K. (2016) Grip strength and cognitive abilities: associations in old age. *The Journals of Gerontology: Series B* **71**, 841–8.

Steves C. J., Mehta M. M., Jackson S. H. D. & Spector T. D. (2016) Kicking back cognitive ageing: leg power predicts cognitive ageing after ten years in older female twins. *Gerontology* **62**, 138–49.

Tyrer F., Dunkley A. J., Singh J., Kristunas C., Khunti K., Bhaumik S. *et al.* (2019) Multimorbidity and lifestyle factors among adults with intellectual disabilities: a cross-sectional analysis of a UK cohort. *Journal of Intellectual Disability Research* **63**, 255–65.

Tyrer S. P., Wigham A., Cicchetti D., Margallo-Lana M., Moore P. B. & Reid B. E. (2010) Comparison of short and long versions of the Prudhoe Cognitive Function Test and the K-BIT in participants with intellectual impairment. *Journal of Autism and Developmental Disorders* **40**, 1000–5.

Uhrich T. A. & Swalm R. L. (2007) A pilot study of a possible effect from a motor task on reading performance. *Perceptual and Motor Skills* **104**, 1035–41.

Voelcker-Rehage C., Godde B. & Staudinger U. M. (2011) Cardiovascular and coordination training differentially improve cognitive performance and neural processing in older adults. *Fronties in Human Neuroscience* **5**.

Vogt T., Schneider S., Anneken V. & Strüder H. K. (2013) Moderate cycling exercise enhances neurocognitive processing in adolescents with intellectual and developmental disabilities. *Research in Developmental Disabilities* **34**, 2708–16.

Webber L. S. & McGillivray J. A. (2011) An Australian validation of the Kaufman Brief Intelligence Test (K-BIT) with adolescents with an intellectual disability. *Australian Psychologist* **33**, 234–7.

Westfall D. R., Kao S.-C., Scudder M. R., Pontifex M. B. & Hillman C. H. (2017) The association between aerobic fitness and congruency sequence effects in preadolescent children. *Brain and Cognition* **113**, 85–92.

Accepted 23 August 2021