APPROVAL SHEET

Title of Thesis: INTERACTIVE RELATIONS OF EXECUTIVE FUNCTION, RACE, AND SEX WITH PHYSICAL PERFORMANCE: A LONGITUDINAL INVESTIGATION IN AFRICAN AMERICAN AND WHITE ADULTS

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ABSTRACT

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Daniel K. Leibel, Master of Arts, Human Services Psychology, 2017

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Previous studies have shown robust, direct associations between executive functions (EF) and physical performance, as well as variation in physical performance as a function of race and sex. However, little is known about how EF relates to age-related decline in physical performance during middle adulthood, and whether this association is moderated by race and sex. Using a sample of 1,549 urban-dwelling adults (59.6% female; 59.4% African American [AA]; 39.9% living in poverty; aged 30 to 64 years at baseline) from the Healthy Aging in Neighborhoods of Diversity across the Life Span (HANDLS) study, the present investigation used mixed-effects regression to examine interactive relations among EF, race, and sex with age-related decline in handgrip strength, standing balance, and lower extremity strength and endurance over four to five years. Results revealed significant two-way interactions of (1) race and age, such that Whites experienced greater age-related decline in single-leg balance and right-handgrip strength than AAs; and (2) sex and age, such that men experienced greater age-related decline in lower extremity strength and endurance than women. Additionally, results revealed a significant three-way interaction of EF, race, and age, such that lower EF was associated with different decline trajectories in right handgrip strength between AAs and Whites. Finally, results revealed that lower EF related to poorer left-handgrip strength, single-leg balance, and lower extremity strength and endurance across time points. These findings have implications for screening and intervention strategies targeting individuals at heightened risk for future physical decline, particularly those with lower EF, men, and Whites.

Interactive Relations of Executive Function, Race, and Sex with Physical Performance: A Longitudinal Investigation in African American and White Adults

By

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Introduction

Assessment of physical functioning is critical in the evaluation of older persons in clinical and research settings (Guralnik et al., 1994). Poor performance in key domains of physical functioning is associated with increased risk for age-related disability (den Ouden, Schurmans, Arts, & van der Schouw, 2011) and functional decline (Guralnik & Winograd, 1994; Penninx et al., 1998). Examples of such measures include the Short Physical Performance Battery (Guralnik, 2007) and the Hand Dynamometer Test (Strauss, Sherman, & Spreen, 2006), which measure lower extremity performance and handgrip strength, respectively.

Previous studies have reported variation in physical performance as a function of sociodemographic factors, namely sex and race. Generally, cross-sectional and longitudinal investigations have found that women and African Americans (AAs)[1] have greater vulnerability for poor physical performance and experience more rapid physical decline than men and Whites, respectively (Seeman et al., 1994; Merrill, Seeman, Kasl, & Berkman, 1997; Kennedy, Stratford, Pagura, Walsh, & Woodhouse, 2002; Haas, Kreuger, & Rolfson, 2012). There is an increased need to understand the mechanisms underlying sex and racial disparities in physical function across the lifespan.

Racial disparities in cognitive aging may, in part, explain differences in physical function in older AA and White adults. AAs display poorer performance than Whites across many domains of neuropsychological function (Glymour & Manly, 2008) and cross-sectional and longitudinal research suggests that aspects of cognitive function are implicated in physical performance (Clouston et al., 2013). Likewise, poorer physical functioning is associated with increased risk for subsequent diagnoses of mild cognitive impairment (MCI) and dementia in

[1] See the Appendix for a list of abbreviations and their definitions.

elderly populations (Abbott et al., 2004; Wang, Larson, Bowen, & van Belle, 2006; Auyeung, Lee, Kwok, & Yoo, 2007).

Executive functions (EF), which are self-regulatory cognitive functions involved in the "orchestration of basic cognitive processes during goal-oriented problem-solving" (Roth, Isquith, & Gioia, 2013, p. 105), are involved in the planning and execution of movement (Mirabella, 2014) and are among the strongest cognitive correlates of functional status (Royall et al., 2007). In addition, prospective and cross-sectional investigations have found robust associations between EF and physical performance, including gait speed and balance (Watson et al., 2010; Muir-Hunter et al., 2014). The association between EF and physical performance may reflect, in part, shared underlying neurobiological mechanisms, such as white matter (WM) status (Parihar, Mahoney, & Verghese, 2013).

To my knowledge, no studies have investigated the longitudinal association of EF abilities and physical function using linear mixed-effects model procedures, which have statistical advantages over more traditional approaches to longitudinal data analysis. In addition, previous prospective investigations of EF and physical function decline have utilized samples of older persons, limiting our understanding of these associations at earlier periods in the adult lifespan. Furthermore, the role of sociodemographic factors in the prospective association of EF and physical performance has not been explored, despite substantial evidence of sex and racial disparities in age-related physical decline.

The proposed study examined interactions of EF, race, and sex with change in physical performance over approximately four to five years within a sample of AA and White urban-dwelling adults aged 30 to 64 years at baseline. Domains of physical performance that were assessed included handgrip strength, balance, and lower extremity strength and endurance.

This thesis first reviews the literature pertaining to physical performance and sociodemographic factors. Next, an overview of the literature on relations of EF with physical performance is provided. The overview is followed by a discussion of potential shared underlying neurobiological mechanisms that may explain the association between EF and physical performance, as well as sex and racial disparities in age-related physical function. After that, specific aims, hypotheses, methods, and data analytic procedures are detailed. Finally, results are presented and discussed, followed by implications and conclusions.

Literature Review

Physical Performance.

Physical performance measures were developed to objectively evaluate key aspects of physical functioning (Guralnik & Winograd, 1994). These assessments are very appealing because they directly measure domains of physical function that would otherwise have to be measured through self- or proxy-report (Guralnik & Winograd, 1994). Objective assessment of physical performance may potentially identify older persons who are in the preclinical stages of disability (Guralnik et al., 1995). Whereas self-report inventories can indicate disability status, objective physical performance measures indicate functional decline that precedes disability (Guralnik et al., 1994).

Physical performance measures have been proposed as easily accessible "vital signs" in the screening of older persons for risks and disorders of which they are unaware (Studenski et al., 2003). Poorer scores on these measures predict subsequent disability (den Ouden et al., 2011), hospitalization (Penninx et al., 2000), and all-cause mortality (Guralnik et al., 1994; Gale, Martyn, Cooper, & Sayer, 2007) in the general population of older adults. In one prospective study of initially healthy middle-aged men, Rantanen et al. (1999) found that midlife handgrip strength was highly predictive of disability 25 years later.

Past research has demonstrated the utility of physical performance measures in tracking functional decline associated with various psychological and physical disorders, such as depression (Penninx et al., 1998) and peripheral arterial disease (McDermott et al., 2006). Performance measures of lower extremity function may also identify older adults who are at heightened risk for falls (Ward et al., 2015). Fried and colleagues (2001) specify weak handgrip strength and slow gait in their criteria for frailty, a highly prevalent clinical syndrome believed to confer heightened risk for adverse outcomes (including mortality) in older persons (Kulmala, Nykänen, & Hartikainen, 2014).

Ample evidence supports the use of physical performance assessments to measure risk for a variety of adverse health outcomes in both research and clinical settings. In addition to these applications, researchers have used these assessments to measure variation in physical performance as a function of sex and race.

Physical Performance and Sociodemographic Factors.

Physical performance varies as function of sociodemographic factors, namely sex and race. Cross-sectional investigations of sex differences have frequently found that older women are at higher risk for poor physical performance than older men (Ferrucci et al., 2000; Penninx et al., 2000). In addition, studies that have assessed age-related disability through both self-report and objective measures have found a greater prevalence of disability in older women than men (Guralnik et al., 1994; Merrill et al., 1997; Kennedy et al., 2002).

In a cross-sectional investigation of older adults, Murtagh and Hubert (2004) found that disability-related health conditions explained a large proportion of sex differences in self-reported disability. Such conditions included greater prevalence of fractures, osteoporosis, osteoarthritis, and depression in older women than in men. In one of the few studies to examine sex differences in physical performance in middle-aged adults, Hansen and colleagues (2014) found that women performed significantly more poorly on all physical performance measures than men.

Likewise, longitudinal studies have reported differential patterns of physical function decline in men and women. Sex differences in lower extremity function may grow more pronounced as people age, such that women exhibit sharper declines than men (Penninx et al., 2000; Seino et al., 2014; Cooper et al., 2011). These trends are less consistent for handgrip strength; some studies have found widening sex differences with age (Bassey & Harries, 2011) while others found narrowing differences (Cooper et al., 2011).

Botoseneanu, Allure, Gahbauer, and Gill (2013) proposed that more rapid decline in lower extremity function for aging women than men may be explained, at least in part, by mortality bias which is not accounted for in most studies. In other words, unhealthy men may die early, whereas unhealthy women may experience functional decline while living longer. Indeed, the researchers found that older men experienced sharper decline in lower extremity function than women after adjusting for mortality bias. Despite these preliminary findings, further evidence is needed to determine whether mortality bias explains sex differences in physical performance decline.

In addition to sex differences, persistent racial disparities in disability exist in older adults, with the prevalence of disability higher among AAs than Whites. Furthermore, the prevalence of many age-related chronic diseases (e.g., hypertension, diabetes, arthritis) is greater in AAs than Whites, as well as poorer functional status associated with those diseases (Kington & Smith, 1997).

Likewise, cross-sectional and longitudinal studies report racial disparities in direct measures of physical function. AAs of both sexes are at heightened risk for poor lower extremity functioning compared with Whites. Cross-sectional studies have reported that, on average, AAs exhibit poorer performance on measures of balance, gait, and lower extremity strength than Whites (Seeman et al., 1994), as well as lung function (Haas et al., 2012). On the contrary, published findings for grip strength typically demonstrate that AAs have stronger grips than Whites (e.g., Newman et al., 2003; Kurina et al., 2004; Rantanen et al., 1994). However, these patterns vary and may attenuate considerably as a function of key moderating factors, including muscle mass (Newman et al., 2003), sex and socioeconomic status (SES) (Thorpe, Simonsick, Zonderman, & Evans, 2016), and whether individuals are U.S.- or foreign-born (Haas et al., 2012).

De Leon and colleagues (2005) longitudinally tracked differences in physical performance decline as a function of race and sex over the course of ten years. Results showed that AAs exhibited poorer lower extremity function at baseline than Whites and that these disparities increased over time, such that AAs experienced sharper declines in performance. Interestingly, racial differences in self-reported disability scores were attenuated over the same period, suggesting that self-report inventories might underestimate racial disparities in physical decline.

Some degree of evidence suggests that racial disparities in disability (Fuller-Thomson, Nuru-Jeter, Minkler, & Guralnik, 2009) and physical performance (de Leon et al., 2005; Haas et al., 2012) are largely reduced after adjustment for SES. However, significant racial differences may persist after adjusting for SES, especially among women. Indeed, de Leon and colleagues (2005) reported that, in women, racial differences in physical function increased after adjustment for SES.

To my knowledge, there have been no prior examinations of interactions between race and sex with physical performance decline over time. It is plausible that AA women may exhibit the most pronounced physical decline based on existing evidence. Disparities in cognitive aging, namely those of EF, may partly explain the role of race in physical performance decline.

Executive Functions and Physical Performance.

EF are "interrelated cognitive control processes involved in the selection, initiation, execution, and monitoring of cognitive functioning, as well as some aspects of motor and sensory functioning" (Roth, Isquith, & Gioia, 2013, p. 105). The "executive" cognitive control functions are distinguished from the "basic" cognitive functions (e.g., language, visuospatial abilities, motor output) in that they orchestrate these basic functions for the purposes of goal-oriented problem-solving. EF encompass a broad range of cognitive subdomains of function, including inhibition, mental flexibility, emotional control, initiation, working memory, sustained attention, planning, organization, self-monitoring, and problem solving.

Older persons with poorer EF performance are more likely to report difficulty with activities of daily living (ADLs) (Cahn-Weiner, Boyle, & Malloy, 2002; Johnson, Liu, & Yaffe, 2007). Furthermore, Pereira and colleagues (2008) found that executive dysfunction was associated with impaired ability to undertake instrumental ADLs (IADLs) (behaviors necessary to live independently) across groups of older adults with Alzheimer's disease (AD), MCI, and without a diagnosis of cognitive impairment. In a meta-analysis of the cognitive correlates of functional status, Royall and colleagues (2007) found that EF performance explained more variance in functional status than all other cognitive domains, including memory and visuospatial abilities, and only explained less than tests of global cognition. A more recent systematic review and meta-analysis determined that EF measures are stronger predictors of falls in the elderly than are tests of global cognition (Muir, Gopaul, & Odasso, 2012).

The role of cognition in physical performance outcomes is well documented (Clouston et al., 2013). Specifically, EF are involved in the planning and execution of motor function (Mirabella, 2014). A direct association between gait speed and EF has been clearly demonstrated in the literature (Yogev-Seligmann, Hausdorff, & Gilati, 2008; Parihar, Mahoney, & Verghese, 2013). Slower and more irregular gait is associated with poorer EF abilities in older adults, and this relation grows more robust with increasingly complex walking tasks (Yogev-Seligmann et al., 2008). Dual-task designs have demonstrated that gait typically slows when either healthy or neurologically impaired participants are asked to complete a second, cognitively demanding task while walking (Yogev-Seligmann et al., 2008). Together, these findings suggest that walking is not an automatic behavior, but rather demands sustained attention, a component of EF.

Cross-sectional investigations have found that EF abilities are related to performance in balance and lower extremity strength in older (Muir-Hunter et al., 2014; Liu-Ambrose, Pang, & Eng, 2007) and middle-aged adults (Malmstrom, Wolinsky, Anderson, Miller, & Miller, 2005). Prospective studies of older adults have demonstrated that EF abilities may significantly predict declines in physical performance over time, specifically gait and balance (Buchman, Boyle, Leurgans, Barnes, & Bennett, 2012; Gothe et al., 2014).

Furthermore, it is plausible that racial disparities in cognitive aging, specifically with reference to EF, may be implicated in different trajectories of physical function between AAs and Whites. AAs typically exhibit poorer performance than Whites on neuropsychological tests across many domains (Glymour & Manly, 2008), including EF (Brewster et al., 2014). Racial disparities between AAs and Whites in cognitive aging have been partially explained by various disadvantages experienced by AAs, including socioeconomic position, geographic segregation, and discrimination (Glymour & Manly, 2008). Indeed, Brewster and colleagues (2014) demonstrated that significant racial differences in EF were eliminated when controlling for life experience variables, particularly literacy and late-life recreational activity. However, it should be acknowledged that our understanding of the measurement issues and explanatory mechanisms that explain poorer performance among AAs on neuropsychological testing remains limited.

In light of the considerable evidence suggesting that EF are crucial in the planning and execution of motor function, it is plausible that EF may moderate the associations of race and sex with physical performance, such that AA women with lower EF would be most vulnerable to physical decline. This hypothesis receives further support from potential overlapping pathophysiology between EF and physical performance impairments within the subcortical and periventricular WM.

Neurobiological Links and Mechanisms.

The association between EF and physical performance may reflect, at least in part, a shared underlying pathophysiology (Parihar et al., 2013). Whereas considerable evidence supports the role of EF in the planning and execution of motor function (Mirabella, 2014), Parihar and colleagues (2013) postulate that the association between EF and gait impairments in the elderly may reflect the presence of lesions resulting from vascular burden within the subcortical and periventricular WM. Indeed, the role of EF as a mediating variable between WM status and physical performance is plausible.

A vast literature provides evidence for a close association between EF abilities and the frontal lobes (Roth et al., 2013), including areas of the prefrontal cortex (PFC). Lesions within discrete frontal cortical areas including the dorsal lateral PFC and orbitofrontal cortex are associated with deficits in the EF domains of mental flexibility (Milner, 1963) and inhibitory control (Berlin, Rolls, & Kischka, 2004), respectively. Generally, anterior areas of the frontal lobes (i.e., the PFC) are implicated in self-regulatory functions and posterior areas in reasoning processes (Yogev-Seligmann et al., 2008).

EF abilities are vulnerable to WM hyperintensities (WMH), or locations of vascular burden within WM that can disrupt signaling between brain areas (Gunning-Dixon & Raz, 2000). In a meta-analysis, Gunning-Dixon and Raz (2000) revealed that greater prevalence of WMH is associated with poorer cognitive performance across domains, with EF abilities and processing speed disproportionately affected compared to immediate and delayed memory. Another meta-analysis found that WMH are associated with faster declines in EF and global cognitive performance in older persons, as well as increased risk of stroke, dementia, and death (Debette & Markus, 2010).

In another study of older adults with a broad range of cognitive function (normal, MCI, and dementia), Tullberg and colleagues (2004) examined the association of WMH with brain regional glucose metabolism, regional cortical atrophy, and cognitive dysfunction. Overall, the researchers found greater prevalence of WMH in frontal regions than in parietal and occipitotemporal regions. In non-demented participants, WMH in any brain region were associated with frontal glucose hypometabolism, as well as poorer scores on tests of EF. EF scores represented a composite of tests measuring initiation-perseveration, auditory and visual working memory, and verbal fluency. These findings suggest that the presence of subcortical ischemic vascular disease at any location in the brain is related to frontal lobe dysfunction.

In a similar vein, a recent systematic review and meta-analysis found that three commonly used EF measures (i.e., Wisconsin Card Sorting Test, Phonemic Verbal Fluency, and Stroop Color Word Interference Test) are sensitive, but not specific, to frontal lobe damage (Alvarez & Emory, 2006). Whereas patients with frontal lobe damage typically perform more poorly on these tests than those without brain damage, conflicting reports exist as to whether persons with non-frontal damage are equally impaired on such tests. The authors suggest that the frontal lobes are likely the greatest contributors to EF tasks, while damage to other brain regions may negatively influence executive processes.

In addition to EF abilities, WM status is also implicated in physical function. Inzitari and colleagues (2007) reported that independent older persons with severe age-related WM changes (ARWMC) had two-fold greater odds of becoming more dependent in IADLs than those with mild ARWMC at one-year follow-up. Likewise, Rosano and colleagues (2005) found that in a sample of older adults with no global cognitive impairment, severity of WMH predicted declines in gait speed, lower extremity strength and endurance, and self-reported ADLs over a period of four years.

Older persons with impaired mobility are more likely to have WM signaling abnormalities (WMSA) as measured by magnetic resonance imaging (MRI) (Guttman et al., 2000). More specifically, WMSA within the frontal and occipitoparietal periventricular WM relate to impaired mobility (Benson et al., 2002). Evidence suggests that accelerated accumulation of such disease-related WMSA over time within these periventricular WM regions may be associated with more rapid mobility declines in a subset of the older population (Wolfson et al., 2005).

Other researchers have found that AAs and women are at heightened risk for WMH compared with Whites and men, respectively. Liao and colleagues (1997) found that while AAs had fewer WM lesions (WML) than Whites, on average, AAs had significantly greater numbers of severe WML. Similarly, Nyquist and colleagues (2014) found that, among adults with first-degree relatives who had early-onset coronary disease, the brains of AAs contained greater deep WML volumes than those of Whites. In a brain imaging study of older men and women, de Leeuw and colleagues (2001) found that women had significantly more periventricular WML and subcortical WML, the latter of which was mainly driven by differences in frontal WML lesion volume. In addition, age was directly related with WML frequency, although no significant interactive relation of age and sex with WML was found.

It is plausible that age-related sex and racial disparities in physical function may, in part, be explained by WM status. Furthermore, given the role of EF in the planning and execution of movement, it is possible that EF mediates associations between WM status and physical performance. Although no research has reported sex differences in EF amongst older persons, AAs and women may be more vulnerable to EF-related declines in physical performance because of disproportionate WM burden.

To my knowledge, prior studies have not directly examined whether the relations of EF to physical performance are explained by WM status, nor have WML been implicated in sex or racial disparities in physical performance. However, given (a) the role of EF in the planning and execution of physical functioning; (b) pronounced racial and sex differences in age-related physical decline; and (c) racial and sex differences in WML (a known correlate of EF), the present study examined potential interactive relations of EF, race, and sex with physical performance decline over time.

Present Investigation

The objective of the present study was to examine potential interactive relations of EF, race, and sex to age-related change in physical performance in AA and White adults through linear mixed-effects regression model analyses. The literature offers robust support for a role of EF in the planning and execution of physical function, as well as evidence of sex and racial disparities in physical performance. In addition, potential explanatory neurobiological mechanisms have been proposed, such that underlying WM pathophysiology may be implicated in EF-related physical function, as well as sex and racial disparities in physical decline. However, the longitudinal association of EF and physical performance has not been previously studied through linear mixed effects regression, and interactions of EF, race, and sex to physical performance, while plausible, have yet to be examined. In addition, most prior literature in this area utilized samples of older adults, whereas the present study examined these trends in a diverse sample of middle-aged adults (aged 30 to 64 years at baseline), thus adding to our understanding of these trends at earlier periods in the adult lifespan.

Specific Hypotheses.

This thesis project utilized a model construction approach in which lower-level interaction terms were retained as higher-level interaction terms were subsequently added to the models (see Data Analytic Plan below). The following hypotheses adhere to this chronology. First, I hypothesized that EF, race, and sex would each interact with age (indexing time) to significantly predict physical performance outcomes, such that lower EF, AA race, and female sex would be associated with greater decline in physical performance over time. Second, I hypothesized that a significant three-way interaction of race, sex, and age would be found such that AA women would experience sharper decline in physical performance over time than White women and men of both races. Third, I hypothesized that significant three-way interactions of (1) race, EF, and age, and (2) sex, EF, and age would be found, such that AA and women with lower EF would exhibit sharper decline in physical performance than those with higher EF. Finally, I hypothesize that a significant four-way interaction of race, sex, EF, and age would be found such that the greatest age-related physical decline would be observed among AA women with lower EF.

Method

Participants

All participants were enrolled in the Healthy Aging in Neighborhoods of Diversity across the Lifespan (HANDLS) study, a longitudinal, epidemiologic investigation (see Parent Study Procedure). Participants are assessed approximately every four to five years for various psychological, cognitive, and physiological factors.

The baseline HANDLS sample comprised a fixed cohort of approximately 2,800 community-dwelling AA and White adults between the ages of 30 and 64 years, living in one of 13 pre-determined neighborhoods in Baltimore City. Participants in the present study are 1,594 adults (baseline mean age = 48.47 years; 59.6% female; 59.4% AA; 39.9% living below the poverty level) for whom (1) complete relevant sociodemographic (i.e., age, sex, race, poverty status, literacy), anthropometric (i.e., body mass index [BMI]), and cognitive test performance (i.e., all EF tests that comprise the composite variable described below in Measures), and (2) at least one physical performance outcome was available Wave 1 or 3. Participants were excluded from the present analyses if they indicated a history of AD or other form of dementia, stroke, or other neurological disorder (i.e., multiple sclerosis, Parkinson's disease, or epilepsy).

Parent Study Procedure

HANDLS is an interdisciplinary, longitudinal, epidemiologic study conducted by the Health Disparities Research Section of the National Institute on Aging Intramural Research Program (for more information on the HANDLS study design, see Evans et al., 2010). The primary aim of HANDLS is to examine contributing factors to persistent age-related disparities in health and disease attributable to race and SES.

Participants were recruited from 13 census tracts in Baltimore City, which were pre-determined for their probability of yielding representative samples of adults from a diverse range of socioeconomic backgrounds. Specifically, researchers sought equal proportions of individuals aged 30 to 64 years old who were AA and White, men and women, and living below and above 125% of the federal poverty line. The HANDLS study commissioned a federal contractor to gather information on residential households within each census tract. Field interviewers invited one to two participants from each identified residence to participate in the study.

Individuals consented to participate and completed a household survey to obtain demographic information, psychosocial measures, and dietary and nutritional measures. Within one day to six weeks later, participants were scheduled to meet with a doctor or nurse practitioner on a Mobile Medical Research Vehicle (MMRV) within their neighborhood. On the MMRV, participants provided information regarding their medical history, underwent a comprehensive physical examination, and completed a series of physical performance measures and neuropsychological tests.

HANDLS data collection is ongoing and participants are reevaluated approximately every four to five years. The present study analyzed data from baseline measurement, (HANDLS Wave 1) and from the second time of complete data collection, four years later (HANDLS Wave 3).

Measures

Executive Function Composite Measure

An EF composite score was computed that encompassed neuropsychological tests of auditory attention, working memory, mental flexibility, and verbal fluency. As discussed, current knowledge suggests that the association between EF and physical performance may reflect WM status, rather than specific neural correlates to subdomains of function. Therefore, it is important to assess a broad construct of EF including a variety of measures, a practice employed by other researchers in this area (Tullberg et al., 2004).

The summation of standardized scores from five neuropsychological tests of EF, computed from the means of the raw scores, will comprise the EF composite. These tests are the Brief Test of Attention (BTA), Trail Making Test (TMT) Part B (TMT-B), Digit Span Forward (DSF), Digit Span Backward (DSB), and Verbal (Semantic) Fluency. Participants completed each test as part of a neuropsychological assessment on the MMRV during both times of data collection. Psychometric properties of each test are discussed.

Brief Test of Attention

The BTA (Schretlen et al., 1996) is an easily administered measure of auditory attention, and has been used as a measure EF (DePrince, Weinzierl, & Combs, 2009). The test is theory-based and was developed to reduce the influence of confounding factors on the measurement of attention (Strauss et al., 2006).

Following BTA guidelines (Schretlen et al., 1996), participants were presented with two parallel forms (Forms N and L) of numbers and letters via audio recording that contained ten lists increasing from 4 to 18 items. Participants were instructed to listen and count the numbers while disregarding the letters when presented with Form N. Conversely, participants counted the letters and disregarded the numbers when presented with Form L. Participants were not instructed to recall which numbers and letters were presented (as in digit span tasks), but rather report how many numbers or letters were presented in each list. The score is the number of correctly monitored lists summed across both forms.

The BTA has high internal consistency ($\alpha = .80$) and low to moderate test-retest reliability ($r = .45$ to $r = .78$), with minimal practice effects (Strauss et al., 2006). Criterion-related validity of the BTA are supported by its strong association to other tests of attention over tests of other neuropsychological domains (Schretlen et al., 1996). The BTA accounts for significant variance in functional competence in patients with severe mental disorders and is significantly related to psychosocial outcomes in adults with traumatic brain injuries (TBI), indicating strong ecological validity (Strauss et al., 2006).

Trail Making Test-Part B

The TMT was originally included within the Army Individual Test Battery in 1944 and has since been adapted as a standalone test of divided attention, speed, and mental flexibility (Strauss et al., 2006). The TMT consists of two sections. TMT-Part A (TMT-A) measures visuomotor tracking and scanning, and TMT-Part B (TMT-B) measures cognitive flexibility through set shifting. Participants completed both TMT-A and TMT-B as part of the HANDLS protocol. Only TMT-B scores will be included in the present study's EF composite score and analyses.

Participants first completed the TMT-B practice sample, which consisted of a page containing both numbers and letters. The examiner instructed participants to begin at number 1 and draw a line to letter A, then continue onto number 2, and continue alternating numbers and letters (1 to A, A to 2, 2 to B, etc.). Participants then completed the TMT-B test, which follows the same instruction as the sample and continues on through number 13, totaling 25 circles. If participants made an error, the examiner instructed them to return to the last circle and correct the error. Time to complete TMT-B and the number of errors made were recorded. The time to completion, in seconds, will be standardized and included in the EF composite score.

Greater age, lesser education, and AA race/ethnicity predict poorer performance on TMT-B, with no reported gender effects (Strauss et al., 2006). Tombaugh (2004) reported that age and education accounted for 35% and 7% of the variance in TMT-B scores, respectively. Most studies have found adequate to high test-retest reliability of TMT-B, with reliability coefficients usually above .60 and often higher (Strauss et al., 2006). However, practice effects make TMT-B test-retest reliability difficult to measure. Alternate form reliability is high at .92 (Strauss et al., 2006).

Kortte, Horner, and Windham (2002) determined that TMT-B is sensitive to cognitive flexibility, as compared to perseverative errors on the Wisconsin Card Sorting Test (WCST). TMT-B scores also correlate to other tests of set shifting, attention, and processing speed (Strauss et al., 2006). TMT-B is also sensitive to TBI, with completion times increasing with increasing head injury severity (Strauss et al., 2006).

Digit Span Forward and Backward

DSF and DSB are subtests from the Wechsler Adult Intelligence Scale-Revised. They require attention and working memory, which are both implicated in executive control functions

(Lezak, Howieson, & Loring, 2012). For DSF, participants listened to a span of numbers read aloud by the examiner, beginning with three digits, and were asked to repeat the numbers back in the same order immediately. After two trials of a specific span length, the span increased by one digit, continuing through nine digits. The test ended when participants could not successfully complete two trials of the same span length. DSB was administered similarly, except participants were instructed to repeat the span of digits aloud in reverse order. DSB started with two-digit spans and continued through eight digits.

Lezak and colleagues (2012) wrote that other than each requiring auditory attention and short-term retention capacity, DSF and DSB require different mental activities and reflect brain damage differently. DSF is primarily a test of attention rather than working memory and is not affected by many brain disorders. DSF may fall below normal limits in the months following TBI, but will likely return to normal levels. This test is among the most resistant in mild stages of dementia. Normal range of DSF is 6±1.

In contrast, DSB is a purer test of working memory and is highly sensitive to many brain disorders (Lezak et al., 2012). The task requires the memory and reversing operations to occur simultaneously. Additionally, mental imagery is implicated in performing this task, with many test-takers mentally lining up the digits and reading them back. The test is especially sensitive to left hemisphere damage and visual field defects. Frontal lobe lesions also lower reverse span. Scores of 4 or 5 are considered within normal limits.

In a confirmatory factor analysis, Burton and colleagues (2003) reported that DSF and DSB had respective factor loadings of .67 and .71 on a Working Memory Factor in two clinical and standardized samples of adults. Snow and colleagues (1989) found Digit Span tests to have strong test-retest reliability, with a coefficient of .89.

Verbal (Semantic) Fluency

Semantic fluency tests require executive strategies of clustering (e.g., retrieving stored mammal names) and set shifting to different clusters (e.g., shifting to birds when mammals are exhausted) and thus are considered to be tests of EF (Strauss et al., 2006). Poor performance on semantic fluency tasks can result from either deficits in stored knowledge or from inefficient search strategies. Participants completed a Semantic Fluency test in which they were instructed to name as many animals as possible within one minute. Scores on this task were the sum of all admissible words (i.e., names of animals). Perseverations and errors were not counted in the total score.

Greater age, lesser education and literacy are associated with poorer performance on Semantic Fluency tests (Strauss et al., 2006). There is also an effect of race/ethnicity, such that being AA is associated with poorer performance on these tasks even after accounting for SES, education, and literacy (Alvarez & Emory, 2006). As with other neuropsychological tests, our mechanistic understanding of these disparities is not sufficient. Fillenbaum et al. (2001) found that AAs living in Indianapolis exhibited stronger performance on Semantic Fluency than AAs in North Carolina, perhaps reflecting disparities in quality of education.

Internal consistency and test-retest reliability for semantic fluency tests are high, even over intervals of many years (Strauss et al., 2006). Scores on these tasks correlate with tests of working memory (Rosen & Engle, 1997). Consistent with its use as a measure of EF, semantic fluency tests are sensitive to individuals with focal frontal TBI lesions (Henry & Crawford, 2004). Despite being one of the most commonly administered measures of EF (Alvarez & Emory, 2006), semantic fluency scores also correlate highly with tests of semantic memory as might be expected (Strauss et al., 2006).

Physical Performance Outcome Measures.

Five measures of physical performance served as dependent variables in the present study. The Grip Strength Test measured left- and right-handgrip strength, tandem and single-leg Stands measured standing balance, and the Ten Times Sit-to-Stand measured lower extremity strength and endurance. Results from physical performance tasks were collected on the HANDLS MMRV at both times of data collection.

Handgrip Strength Test

Handgrip strength was assessed using a Hand Dynamometer, an instrument which measures maximum force of voluntary grip movements for both hands in kilograms (Strauss et al., 2006). Handgrip strength is frequently assessed to determine the integrity of motor function (Strauss et al., 2006) and estimates the overall strength of the upper body skeletal muscle (Haas et al., 2012). Furthermore, handgrip strength is considered a general marker of physical frailty (Fried et al., 2001; Syddall et al., 2003).

Participants were asked whether they had surgery on either of their hands or wrists in the last three months, as a basis for not measuring that hand. Participants were also asked to indicate whether they had any current pain or arthritis flare-ups in their hands or wrists; if deemed safe and willing, participants were allowed to continue with the task. Participants indicated whether they were right-handed, left-handed, or ambidextrous.

Participants were asked to squeeze the two bars of the dynamometer together as hard they could until instructed to relax seconds later. The examiner first demonstrated the task and then the participant practiced without full force. Participants completed two trials for each hand, with at least 15 to 20 seconds rest in between trials, while in a seated position with their arm resting on a table in an extended position. Scores were calculated from the means of the maximum force recorded between each of the two trials for each hand.

According to numerous reports, Grip Strength has an inverse relation with age, with disagreement about the age of decline onset (Bornstein, 1985; Thompson et al., 1987). Bornstein (1985) reports a significant effect of education, whereas others have failed to replicate this finding (Strauss et al., 2006). It is well-documented that males outperform females on the hand dynamometer test (Nicolay & Walker, 2005).

Grip Strength has high test-retest reliability and strong ecological and predictive validity (Strauss et al., 2006). Strauss and colleagues (2006) report that published Grip Strength test-retest reliability coefficients in both normal and neurologically impaired individuals range from .52 to .96, and most are greater than .70. Grip Strength is sensitive to aging (Frederiksen et al., 2006) and is related to functional impairments in ADLs in older adults (Femia, Zarit, & Johannsen, 2001). This test is useful in the detection of brain damage, specifically contralateral lesions (Strauss et al., 2006). Norms assume intra-individual superior performance in the dominant hand, but these are complicated due to the extensive variability in non-dominant to dominant hand strength ratios in the general population (Strauss et al., 2006).

Tandem Stand

Standing balance was assessed using the tandem stand measure, which is one of three balance measures in the Short Physical Performance Battery (Guralnik, 2007) and adds complexity to the task of balance by narrowing the base of support (Franchignoni, Tesio, Martino, & Ricupero, 1998). Participants are instructed to stand upright with their arms folded across their chest, with their dominant foot just in front of their other foot. The score is the number of seconds participants are able to maintain the stand (maximum of 30 seconds), with longer durations indicating stronger balance performance.

Test-retest reliability of Short Physical Performance Battery balance scores (which includes the tandem stand), is considered moderate to high in community samples (coefficients .55 to .84) (Freire, Guerra, Alvarado, Guralnik, & Zunzunegui, 2012; Ostir, Volpato, Fried, Chaves, & Guralnik, 2002). Franchignoni et al. (1998) report strong test-retest reliability of the tandem stand alone (r = .90). Friere and colleagues (2012) found that tandem stand balance scores were significantly associated self-reported difficulty in climbing stairs, kneeling, weightlifting, and walking one mile, as well as level of self-reported disability in a diverse community sample of older adults.

Single-Leg Stand

The single-leg stand was completed as a second measure of standing balance to add complexity to balance tasks. This test required participants to stand on either one leg with their other leg lifted off the ground. The length of time from when the participant lifted their leg from the ground to when they returned it to the ground was recorded, with a maximum time of 30 seconds. The score was the average time across three trials.

Lin et al. (2004) reported strong test-retest reliability and discriminant validity of the single-leg stand in older community-dwelling populations comparable with other measures of balance and mobility.

Ten Times Sit-to-Stand

Lower extremity strength and endurance was measured through the Ten Times Sit-to-Stand task. Participants are timed as they stand up and return to a seated position ten times as quickly as they can, without the assistance of their arms. Score is the time in seconds that it takes participants to complete all ten stands, with shorter times indicating better performance and stronger lower extremity strength and endurance abilities.

Test-retest reliability of the Ten Times Sit-to-Stand task has been found to be moderate to high (.67 to .78) (Jette et al., 1999; Friere et al., 2012). In older adults, poorer performance on repeated chair stand tasks relates to greater risk of self-reported disability, as well as more reported difficulties in moving an armchair, weightlifting, climbing a flight of stairs, walking one mile, and kneeling (Friere et al., 2012).

Covariate Measures.

Poverty Status

Participants self-reported their annual income during both occasions of data collection and were classified as either above or below 125% of the Federal poverty line as an indicator of poverty status.

Body Mass Index

BMI was calculated by dividing participants' weight in kilograms over the square of their height in meters (Centers for Disease Control and Prevention, 2015) and was collected on the HANDLS MMRV at both times of data collection. BMI is significantly associated with objective measures of physical performance (Schoffman, Wilcox, & Baruth, 2013; Shen et al., 2015).

Wide Range Achievement Test-3: Word Reading

Quality of education may vary widely between individuals with the same level of education as measured by years in school. Indeed, validly measuring educational attainment through number of years in school in socioeconomically diverse samples is complicated. Therefore, total scores from the Reading subtest of the Wide Range Achievement Test-3

(WRAT-3; Wilkinson, 1993) will adjust for literacy effects. Participants completed WRAT-3 Reading as part of a larger neuropsychological assessment at both occasions of data collection.

The WRAT-3 Reading subtest has strong internal consistency measured through alternate form reliability (Strauss et al., 2006). Across age groups, median alternate form reliability is estimated at .95. In adults with TBI, test-retest reliability over one year is high at .88 (Orme, Johnstone, & Hanks, 2004). The WRAT-3 Reading subtest is among the top ten tests used by neuropsychologists and is the most widely administered reading test in adult neuropsychological evaluations (Strauss et al., 2006).

Data Analysis

Power Estimate.

Power analysis was conducted using the G*Power 3.1.9.2 statistical software. The sample of 1,594 participants with 10 predictors (including all two-way interaction terms and covariates from the first model in each series of analyses) is powered ($1-\beta = .99$) to detect a small to medium Cohen's f^2 effect size of .030 at conventional levels of alpha (.05). Analysis-specific sample sizes varied depending on the outcome variable of interest. Results from the power analysis predicted that power would not attenuate at the smaller sample sizes and that detection of a small f^2 effect size was as likely as in the larger samples. For the longitudinal analyses, addition of 3 more two-way interaction terms (EF × age, race × age, sex × age) to the model did not attenuate power estimates.

Specific methods for accurately predicting statistical power for linear mixed-effects model analyses have yet to be developed and disseminated, in part due to the complexities of such designs. Nevertheless, the present power analysis may be presumed to underestimate the actual likelihood of rejecting a false null hypothesis, given that increasing the number of data points relevant to sample size is associated with enhanced statistical power.

Data Analytic Plan.

Descriptives

Prior to any analyses, descriptive statistics among all outcome variables were computed. These analyses were further evaluated for normality, skewness, outliers, and multicollinearity. Variable distributions were visualized through histograms and Q-Q plots. Logarithmic-transformations were conducted to normalize skewed distributions of any variables. If logarithmic-transformations failed to resolve the skewness of a distribution, then the variables were dichotomized and analyzed through binary logistic mixed-effects regression (see below).

Linear Mixed-Effects Models Analyses

Analyses were conducted using the 'lme4' package within RStudio 1.0.143. Mixed-effects regression models were conducted to test hypotheses regarding prospective interactive relations of EF, race, and sex with physical performance. This statistical approach to analysis of longitudinal data was selected over more traditional approaches (e.g., repeated-measures analysis-of-variance [rmANOVA]) because it more efficiently handles inconsistent measurement intervals across participants, allows for specification of time-variant covariates, and can better accommodate missing data and attrition that are common in prospective studies that track participants over time (Gueorguieva & Krystal, 2004; West, 2009).

As described in detail below (see Results), Q-Q plots revealed non-normal, negatively skewed distributions for the tandem stand and single-leg stand balance tests. Logarithmic-transformations failed to remediate the skewed distributions. Therefore, given their distributions, decisions were made to (1) recode single-leg balance as a dichotomous variable and analyze the hypothesized associations using logistic mixed-effects regression and (2) exclude the tandem stand variable from analysis. This process is described in detail in the Results section.

As discussed, the proposed study utilized a model construction approach to data analysis such that lower-level interactions were retained as higher-level interactions were subsequently added to the models. When the highest-level significant interaction was identified, it was retained along with lower-order interaction terms nested beneath (irrespective of significance). Lastly, non-significant lower-order interactions that were not nested beneath the highest-order interaction were removed from the final model. This process of retaining significant higher-order effects while removing non-significant effects, also known as trimming, is similar to the backward-elimination procedure described by Morrell and colleagues (1997). Each of the four physical performance outcome measures (right- and left-handgrip strength, single-leg stand balance, and Ten Times Sit-to-Stand) were entered as individual dependent variables in separate models. In total, three distinct linear mixed-effects regression models and one logistic mixed-effects regression model were analyzed. Age was specified as a random effect to index time, as seen in prior studies with similar designs (Wendell, Zonderman, Metter, Najjar, & Waldstein, 2009; Waldstein et al., 2008). EF, race, sex, and their interactions were modeled as fixed effects. Interactions of EF, race, and sex with age, representing change over time, were also modeled as fixed effects.

BMI and literacy scores were treated as continuous covariates and poverty status were treated as a categorical covariate. Furthermore, BMI and literacy scores were specified as time-variant covariates in all analyses, whereas poverty status was specified as a time-invariant covariate in all analyses. Finally, dominant-handedness was included only in analyses where left- or right-handgrip strength were dependent variables. Specifically, dominant-handedness was represented by two time-variant, "dummy-coded," categorical covariates. That is, two categorical variables were used to compare right-handed participants (i.e., the reference group) to (1) left-handed participants, and (2) ambidextrous participants.

Results

Outcome variable distributions.

Preliminary data screening with Q-Q plots demonstrated violations of normality for two of the physical performance outcome variable distributions. As described briefly above, the single-leg stand and tandem stand distributions were heavily negatively skewed, with the majority of participants balancing for the maximum time of 30 seconds. Logarithmic- and square-root transformations failed to rectify these violations, and all distributions remained non-normal. Therefore, it was determined that binary logistic mixed-effects regression would be used to examine interactions of EF, race, sex, and age with change in single-leg and tandem stance balance tasks. Both balance task variables were dichotomized, such that participants were classified into two groups: (0) "Passed balance task" (i.e., held the stand for 30-second maximum time), and (1) "Failed balance task" (i.e., did not hold the stand for 30-second maximum time). Subsequently, it was determined that, across waves, there was sufficient representation of cases who passed (n = 1204, 77.2% of valid cases) and failed (n = 356, 22.8% of valid cases) the single-leg balance task to proceed with analysis. Conversely, it was determined that there was insufficient representation of participants who failed the tandem stand balance task to proceed with analysis (n = 110, 4.0% of valid cases). Therefore, tandem stand balance performance was not analyzed in the present study.

Descriptives.

Table 1 presents sample characteristics in AA women and men, White women and men, and in the overall sample at Waves 1 and 3. In total, there were 1594 participants (59.6% female, n = 950; 40.4% male, n = 644), who met inclusion criteria for the present study. Analysis-specific sub-samples varied according to data available for the particular physical performance outcome of interest (Table 2). Average age at Wave 1 was 48.47 (± 8.96) years (n = 1,322), whereas average age at Wave 3 was 52.98 (± 8.98) years (n = 1,415). Table 3 presents sample characteristics stratified at the mean age at Waves 1 and 3.

Across waves, there were no significant differences between men and women in age, race, poverty status, literacy scores, or dominant handedness. During Wave 1, women (versus men) had significantly greater BMI, $t(320)$-difference = 7.34, $p < .001$, whereas men (versus women) had significantly greater (1) DSF scores, $t(1320)$-difference = 2.288, $p = .022$, and (2) verbal fluency scores, $t(1320)$-difference = 3.04, $p = .002$. During Wave 3, women (versus men) had significantly greater BMI, $t(1411)$-difference = 7.616, $p < .001$, whereas men had significantly greater verbal fluency scores, $t(1413)$-difference = 4.113, $p < .001$.

Correlation Matrix.

Table 4 contains bivariate correlations among all the study variables at Waves 1 and 3.

Linear- and Logistic-mixed effects regression analyses.

As proposed in the Methods section (see Data Analytic Plan), the present study followed a model construction approach to data analysis. That is, main effects and lower-level interaction terms were retained as higher-level interaction terms were subsequently added to the model, with the goal of determining the highest-level significant interaction effects. That is, the highest-level significant interaction effect was identified and retained, along with all lower-order interaction effect(s) nested beneath (irrespective of significance). Lastly, non-significant interactions that were not nested beneath the highest-order significant interaction were removed from the final model. As a result, the final linear and logistic mixed-effects regression models for each outcome of interest contained (1) the highest-level significant interaction effect(s), (2) lower-level interaction effects nested within them, (3) all main effects and (4) all covariates.

Right-handgrip strength.

In total, 1,489 participants completed the right hand dynamometer test during Waves 1 or 3, totaling 2,260 observations across both waves (see Table 2). As demonstrated in Table 5, the model containing all two-way interaction terms revealed a significant two-way interaction of race and age with right-handgrip strength, such that AAs experienced lesser decline in right-handgrip strength than Whites, $B = .09$, $t(2244) = 2.14$, $p = .03$ (Figure 1). However, in a subsequent analysis, this interaction became non-significant and was superseded by a significant higher-order three-way interaction of EF, race, and age, $B = -0.04$, $t(2238) = -2.60$, $p = .009$. As demonstrated in Table 6, the three-way interaction of EF, race, and age with right-handgrip strength remained significant in the final model after the removal of non-significant interaction terms, $B = -0.04$, $t(2244) = -2.60$ $p = .010$. As shown in Figure 2, the interaction revealed differing trajectories of decline in handgrip strength over time as a function of race and EF. Although Whites had similar right-handgrip strength across levels of EF at younger ages, their rate of decline decline diverged for those lower and higher in EF performance; that is, lower EF was associated with greater decline in right-handgrip strength (and greater EF was related to lesser age-related decline). In contrast, findings suggested that, at younger ages, AAs differed as a function of EF in that lower levels of EF were associated with lower right-handgrip strength; however, their rate of decline converged over time such that lower EF was associated with *lesser* decline and greater EF was associated with *greater* decline in right-handgrip strength. Interpreted another way, AAs and Whites with greater EF exhibited approximately equal rates of age-related decline in right-handgrip strength. Conversely, Whites with lower EF demonstrated accelerated right-handgrip strength decline, while AAs with lower EF demonstrated negligible change in right-handgrip strength over time. There were no further significant two-, three-, or four-way interaction effects with right-handgrip strength. In addition, the final model (as well as all other models) revealed a significant main effect of sex, such that men had significantly greater right-handgrip strength than women across time points, $B = 15.78$, $t(2244) = 39.55$, $p < .001$. Lastly, examination of significant covariate effects in the final model revealed that, across time points, lower right-handgrip strength was associated with (1) lower BMI, $B = 0.09$, $t(2244) = 3.51$, $p = .001$; (2) living in poverty, $B = -1.36$, $t(2244) = -3.30$, $p = .001$; (3) lower literacy, $B = 0.06$, $t(2244) = 1.97$, $p = .049$; and (4) left-handedness, $B = -1.22$, $t(2244) = -2.09$, $p = .037$.

Left-handgrip strength.

In total, 1,485 participants completed the left hand dynamometer test, for a total of 2,248 observations across Waves 1 and 3 (see Table 2). As demonstrated in Table 7, results of the linear mixed-effects regression analyses for left-handgrip strength revealed no significant two-, three-, or four-way interaction effects of EF, race, sex, and age with left-handgrip strength (i.e., all p's > .05). As detailed in Table 8, after removal of all interaction effects, four significant main effects were observed, such that greater left-handgrip strength was associated with: (1) increased age, $B = -0.21$, $t(2232) = -0.99$, $p < .001$ (Figure 3); (2) greater EF (across time points), $B = 0.35$, $t(2232) = 4.14$, $p < .001$ (Figure 4); (3) male sex, $B = 16.94$, $t(2232) = 39.78$, $p < .001$; and (4) AA race, $B = 2.42$, $t(2232) = 5.62$, $p < .001$. Lastly, examination of significant covariate effects in the final model revealed that, across time points, lower left-handgrip strength was associated with (1) lower BMI, $B = 0.08$, $t(2232) = 2.90$, $p = .004$; (2) living in poverty, $B = -1.42$, $t(2232) =$

-3.24, p = .001; (3) lower literacy, B = 0.07, $t(2232)$ = 2.35, p = .019; and (4) right-handedness (versus left-handedness), B = -2.33, $t(2232)$ = -3.80, p < .001.

Notably, there was a three-way interaction effect of EF, race, and age with left-handgrip strength that approached statistical significance (p's < .10) in the model that included all two- and three-way interaction terms, B = -.03, $t(2232)$ = 1.69, p = .092 (see Table 7), as well as after backward elimination of other non-significant interaction effects, B = -.03, $t(2232)$ = -1.67, p = .096 (data not shown in a table). When decomposed, the pattern of findings directly paralleled those noted for right-handgrip strength.

Single-leg standing balance.

In total, 1,112 participants completed the single-leg stand during Waves 1 or 3, for a total of 1,558 observations across both waves (see Table 2). As demonstrated in Table 9[2], the model with all two-way interaction effects (as well as the model with all two-, three-, and four-way interaction effects) revealed a significant two-way interaction of race and age with single-leg balance, B = -0.04, z = -2.12, p = .034. However, the models as outlined in the data analytic plan did not converge properly, indicating that results may be invalid. Efforts were made to remediate the problem: (1) as described before, the models were trimmed to remove non-significant interaction terms; (2) at the recommendation of the statistical software, continuous variables were centered at their means; and (3) BMI and poverty status (i.e., covariates in all previous analyses) were removed from the final model. Therefore, the final model included the two-way interaction of race and age, all main effects, and literacy as the sole covariate; ultimately, this final model converged. As demonstrated in Table 10, the two-way interaction effect of race and

[2] Table 9 displays data from all permutations of the logistic-mixed effects regression models for single-leg balance for illustrative purposes. However, only the final model (displayed in Table 10) converged.

age remained significant in the final model, $B = -0.04$, $z = -2.00$ $p = .047$. As shown in Figure 5, increased age was more strongly associated with increased probability of failing the single-leg balance task among Whites than their AA counterparts. In addition, the final model revealed significant main effects of EF and sex with single-leg stand performance across time points, such that higher probability of failing the single-leg stand task was associated with (1) lower EF, $B = -.11$, $z = -3.09$, $p = .002$ (Figure 6); and (2) female sex, $B = -.47$, $p = .002$. Lastly, in the final model, lower literacy was associated with greater probability of failing the single-leg balance task across time points, $B = -.02$, $z = -1.99$, $p = .047$.

Ten Times Sit-to Stand.

In total, 1,372 participants completed the Ten Times Sit-to-Stand, for a total of 2,035 observations across Waves 1 and 3 (see Table 2). As demonstrated in Table 11, the model containing all two-way interaction terms (as well as later models) revealed a significant two-way interaction of sex and age with the Ten Times Sit-to-Stand task, $B = .12$, $t(2019) = 2.94$, $p = .003$. As demonstrated in Table 12, in the final model, the two-way interaction of sex and age remained significant after non-significant interactions were removed, $B = 0.12$, $t(2024) = 2.96$, $p = .003$. Briefly, as shown in Figure 7, results revealed that men exhibited greater decline in lower extremity strength and endurance over time than women. In addition, this model revealed a significant main effect of EF, such that greater EF abilities were associated with poorer lower extremity strength and endurance across time points, $B = -.18$, $t(2024) = -2.12$, $p = .034$ (Figure 8). Finally, examination of significant covariate effects in the final model revealed that, across time points, slower performance on this task was associated with living below the poverty line, $B = 1.59$, $t(2232) = 3.81$, $p < .001$.

Discussion

The purpose of the present study was to examine the interactive relations of EF, race, and sex with age-related change in several domains of physical performance among participants enrolled in the HANDLS study. Examined herein were four dimensions of physical performance including right- and left-handgrip strength, single-leg standing balance, tandem standing balance[3] and lower extremity strength and endurance. It was hypothesized that: (1) lower EF, AA race, and female sex would be independently associated with greater decline in physical performance over time; (2) AA women would experience greater decline in physical performance over time than White women and men of both races; (3) AAs and women with lower EF would exhibit greater decline in physical performance than those with higher EF; and finally, (4) the greatest age-related physical decline would be observed among AA women with lower EF. Results did not support any of the proposed hypotheses. However, findings revealed several significant interactions among EF, race, and sex with age-related decline in physical performance outcomes, albeit not in the hypothesized patterns.

With regard to EF, findings revealed significant main effects of EF with single-leg balance, lower extremity strength and endurance, and left-handgrip strength, such that greater EF was associated with better performance on those tasks. Additionally, findings demonstrated a significant three-way interaction of EF, race, and age with right-handgrip strength, such that age-related trajectories of decline in right-handgrip strength diverged as a function of EF among Whites, but converged as a function of EF among AAs. With regard to sociodemographic differences in physical performance, findings revealed (1) significant two-way interactions of race and age with single-leg balance and right-handgrip strength, such that Whites experienced greater decline in these areas between waves 1 and 3 than their AA counterparts; (2) a significant

[3] As discussed, tandem stand balance performance could not be examined through either linear- or logistic-mixed effects regression (see Results section).

two-way interaction of sex and age with lower extremity strength and endurance, such that men experienced greater decline in this area between waves than women; (3) significant main effects of sex with single-leg balance, right-handgrip strength, and left-handgrip strength, such that men performed significantly better than women on these tasks across time points; (4) a significant main effect of race with left-handgrip strength, such that AAs had stronger left grips than their White counterparts; and (5) a significant main effect of age with left-handgrip strength, such that left-handgrip strength declined between Waves 1 and 3. Lastly, with regard to the effects of covariates, findings revealed (1) significant effects of BMI with right and left-handgrip strength, such that lower BMI was associated with lower grip strength across time points; (2) significant effects of poverty status with lower extremity strength and endurance and right- and left-handgrip strength, such that living below the poverty level was associated with poorer performance on these tasks across time points; (3) significant effects of literacy with single-leg standing balance and right- and left-handgrip strength, such that lower literacy was associated with poorer performance on these tasks across time points; and (4) significant effects of left-handedness with left- and right-handgrip strength, such that being left-handed was associated with greater left- and lower right-handgrip strength, respectively. These findings are discussed in detail below.

Hypothesis 1: EF x Age, Race x Age, and Sex x Age.

The first hypothesis predicted that lower EF, AA race, and female sex would be independently associated with greater age-related decline in physical performance. Results did not support this hypothesis. I will discuss each of the components of these unsupported hypothesis in detail below, as well as significant two-way interaction effects and main effects that were not hypothesized.

EF x Age.

Hypothesis 1 posited that lower EF would be associated with greater age-related decline in physical performance across domains. Results did not confirm this hypothesis. Rather, findings revealed non-significant two-way interaction effects of EF and age for all physical performance outcomes (see below for discussion of a significant three-way interaction of EF, race, and age for right-handgrip strength). These findings are inconsistent with prior longitudinal studies demonstrating that EF is associated with declines in physical performance (Watson et al., 2010; Best, Davis, & Liu-Ambrose, 2015; Atkinson et al., 2007). However, to my knowledge, previous longitudinal studies in this area have typically measured physical performance with gait speed, and none have measured the dimensions of physical function assessed in the present study. Furthermore, such studies have utilized samples of older adults (i.e., 70 years of age or older at baseline), whereas the present study examined middle-aged adults (i.e., between 30 and 64 years of age at baseline).

Although EF was not associated with decline in single-leg balance, lower extremity strength or left-handgrip strength over time, it was significantly related to average levels of performance in these areas across time points. That is, although not explicitly hypothesized, greater EF (across time points) was associated with better performance on the timed-repeated chair stand task and lower probability of failing the single-leg balance task (also across time points). Thus, it is possible that different levels of EF are not associated with decline trajectories until older ages. These findings are consistent with prior literature indicating that EF is closely related to planning and executing movement (Mirabella, 2014) and directly associated with aspects of physical functioning such as gait speed (Yogev-Seligmann et al., 2008; Parihar et al., 2013) and balance (Muir-Hunter et al., 2014; Liu-Ambrose et al., 2007; Malmstrom et al., 2005;

Buchman et al., 2012; Gothe et al., 2014). Results are also generally supported by prior longitudinal and cross-sectional investigations demonstrating that greater decline and poorer performance in EF is associated with decline in overall functional status (Cahn-Weiner et al., 2002; Royall et al., 2007; Johnson et al., 2007) and increased risk for falls in older adults (Mirelman et al., 2012).

Several potential explanatory mechanisms may, at least in part, explain the association of EF with physical performance. In that regard, findings from neuroimaging research suggest that underlying WM pathology is related to both EF and physical performance, namely lower extremity functioning and handgrip strength (Parihar et al., 2013; Gunning-Dixon & Raz, 2000; Yogev-Seligmann et al., 2008; Rosano et al., 2005; Sachdev, Wen, Christensen, & Jorm, 2005). Indeed, it is possible that EF partially mediates significant associations between WM status and physical functioning. As discussed earlier, several studies have found that age-related neuropathology, particularly WM changes, are associated with both EF (Gunning-Dixon & Raz, 2000; Debette & Markus, 2010; Tullberg et al., 2004) and physical performance deficits (Inzitari et al., 2007; Rosano et al., 2005; Guttman et al., 2000). For example, one meta-analysis found that WMH are associated with faster declines in EF and global cognitive functioning in older adults (Debette & Markus, 2010). Another study examining WM status in older adults without cognitive impairment found that declines in gait speed, lower extremity strength, and self-reported ADLs were inversely related to WMH severity (Rosano et al., 2005).

In addition to WM status, several cortical and subcortical gray matter regions may be implicated in the EF-physical performance associations observed in this study. In that regard, Mirabella (2014) notes that EF underlie the genesis, planning, execution, and maintenance of goal-directed movements. For example, the supplementary motor cortex (SMC) - the supplementary motor area (SMA), the pre-SMA, and the supplementary eye field - is a neural region crucial to the planning of movement ultimately initiated by the primary motor cortex (Nachev, Kennar, & Husain, 2008). Nachev and colleagues (2008) reviewed studies in humans and non-human primates that demonstrated a role of the SMC in various aspects of EF, such as response inhibition, set shifting, and initiation. With regard to balance, research has demonstrated a role of the SMA in postural control (Viallet, Massion, Massarino, & Khalil, 1992). Therefore, it is plausible that the SMC influences balance and other areas of physical performance via EF.

Other candidate brain regions that warrant further study in this area include the PFC and basal ganglia. The PFC is the cortical region most frequently coupled with EF in the literature (Elliott, 2003). Indeed, patients with PFC damage exhibit impaired judgment, decision-making, and planning, and perform poorly on neuropsychological tests of EF that require integration of different cognitive domains (Stuss & Benson, 1984). However, other research suggests that EF tests are sensitive, but not specific, to frontal lobe damage (Alvarez & Emory, 2006). Furthermore, although the PFC does not appear to have direct connections with the primary motor cortex, it is indirectly involved in cognitive control over behavior (and therefore physical functioning) via the premotor areas that send information to the primary motor cortex; it further receives motor information from the basal ganglia (Miller & Cohen, 2001).

As described by Graybiel (2000), the basal ganglia comprise the largest subcortical structures of the cerebrum. They receive input from the cortex and send output to frontal cortex by way of the thalamic nuclei, placing them at a prime location to influence the executive and planning motor functions of the frontal lobes (Graybiel, 2000; Monchi et al., 2006). In addition to motor function, the basal ganglia are crucial to aspects of cognitive functioning, including motor learning and memory (Doyon et al., 2009). Furthermore, damage to the basal ganglia in movement disorders, such as Parkinson's disease and Huntington's disease, usually compromises EF (Elliott, 2003). Executive impairments are particularly evident in the early stages of Parkinson's disease when lesions are primarily confined to basal ganglia regions, such as the striatum (Elliott, 2003). Therefore, the basal ganglia may be implicated in EF-physical performance relations, given their relation to cognitive functioning, movement, and movement disorders.

Another possibility is that common neurobiological mechanisms contribute to EF and physical performance simultaneously. That is, shared neurobiological underpinnings might act as a "third variable" that contributes, at least in part, to EF and performance on balance, lower extremity strength, and left-handgrip strength tasks. For example, it is well established that subcortical regions involved in both gait control and balance functions (e.g., thalamocortical and corticospinal tracts), as well as EF (e.g., frontal subcortical WM) are within close proximity of each other within the periventricular WM (Parihar et al., 2013). These subcortical areas become more vulnerable to pathologies with increased age (Bohnen, Bogan, & Muller, 2014), which can have adverse effects on motor and cognitive functioning. It is further plausible that cardiovascular risk factors (e.g., hypertension, tobacco use) that contribute to cerebrovascular disease (Shimada, Kawamoto, Masubayashi, & Ozawa, 1990; Kario et al., 2003; Howard et al., 1998) might damage these neighboring regions (via WMH and silent brain infarcts), thus promoting simultaneous declines in EF and physical function.

Finally, it should be noted that the association between EF and physical performance might be bidirectional, and the present findings cannot establish directionality. Interestingly, Milovic (2016) found that adults randomly assigned to use standing desks while at work (i.e., a physical performance-based intervention) demonstrated improved performance on EF tests compared to a control group that used sitting desks. It is plausible that this physical performance intervention, which required participants to stand while performing a task that is usually performed while seated, activated executive cognitive control systems which ultimately improved performance on neuropsychological tests of EF. There is also growing literature support suggesting that physical activity interventions have a small, but significant positive effect on cognitive, particularly executive, functioning (e.g., Guiney & Machado, 2013; Leckie et al., 2014). Future studies should seek to disentangle the longitudinal and potentially bidirectional relations between EF and aspects of physical functioning, as well as possible mediating factors like physical activity.

Race x Age.

Next, hypothesis 1 posited that AA race would be associated with greater age-related decline in physical performance. Results did not confirm this hypothesis. However, findings demonstrated significant interaction effects of race and age with single-leg balance and right-handgrip strength[4], such that increased age was more strongly associated with declining single-leg balance and right-handgrip strength performance among Whites than their AA counterparts. There have been relatively few longitudinal studies of racial disparities in age-related physical performance decline, and findings from those have been equivocal. For example, with regard to balance, some studies have found that AAs experience greater lower extremity function decline over time than their White counterparts (de Leon and colleagues, 2005; Goodpaster et al., 2006). Conversely, Seeman and colleagues (1994) found non-significant racial differences in decline on the Short Physical Performance Battery. Interestingly, Seeman and colleagues (1994) found that

[4] The significant two-way interaction of race and age with handgrip strength was ultimately superseded by a significant three-way interaction of EF, race, and age with the same outcome (see Results section). However, given the present study's model construction approach, the two-way interaction was interpreted and discussed.

older AAs were more likely to have either decline *or* improvement in physical functioning over three years than older Whites, which may have explained the lack of mean racial differences in physical performance change in that particular study. As such, longitudinal studies have less consensus regarding racial disparities in physical functioning than cross-sectional studies, which have generally demonstrated that, on average, AAs exhibit poorer performance on measures of balance, gait, and lower extremity strength and endurance than Whites (Seeman et al., 1994; de Leon et al., 2005; Clay et al., 2015). One potential explanation for these inconsistencies might be the different demographic samples utilized across studies. For example, the present study examined a sample of adults who were 30 to 64 years of age at baseline, whereas most prior studies in this area have examined older adult samples (i.e., minimum of 65 years old at baseline) (e.g., de Leon et al., 2005; Seeman et al., 1994; Goodpaster et al., 2006). Some studies also used samples that contained a large majority of White participants (e.g., Seeman et al., 1994), while the present sample had relatively equal representation of AA and White participants. As such, the present study's findings suggest that, during middle age, patterns of racial differences in standing balance performance trajectories might vary from those at later periods in the adult lifespan.

To my knowledge, there have been no prior longitudinal studies of racial differences in handgrip strength decline over time, indicating that the present findings represent a unique contribution to the physical performance literature. That said, the present finding that Whites experience greater decline in right-handgrip strength that AAs is generally consistent with cross-sectional literature indicating that AAs have stronger grips than Whites (e.g., Kurina et al., 2004; Rantanen et al., 1994; Newman et al., 2003). Yet, these findings are inconsistent with other cross-sectional and longitudinal studies indicating that AAs are at higher risk for self-reported physical disability than Whites at older ages (de Leon et al., 2005; Fuller-Thomson et al., 2009).

Older AAs (versus older Whites) also have higher rates of frailty, a syndrome associated with increased vulnerability to poor health outcomes in aging and that includes weak handgrip strength in its criteria (Hirsch et al., 2006).

It remains unclear why Whites (versus AAs) in the present study experienced greater decline in single-leg balance and right-handgrip strength performance in middle adulthood. Potential explanatory factors may be found in related literatures which show that AAs (versus Whites) have greater muscle mass (Newman et al., 2003), which relates to physical performance (Janssen, Heymsfield, & Ross, 2002; Visser et al., 2002). Conversely, physical performance is directly related to physical activity (Pahor, 2006), and evidence suggests that AAs are less physically active than Whites (Marshall et al., 2007). Another contributing factor might be the socioeconomic distribution of the present study's sample. As discussed, the present sample was socioeconomically diverse, with high representation of low SES AA and White participants. Other studies examining racial differences in physical functioning had dissimilar sample demographics. For example, de Leon and colleagues (2005), used data from the Chicago Health and Aging Project (CHAP); although the sample had fairly equal representation of AA and White participants from a range of SES backgrounds, adjusted household income was not considered in study recruitment (for details on the study design, see Bienias, Beckett, Bennett, Wilson, & Evans, 2003). Furthermore, as de Leon and colleagues (2005) acknowledge, White participants had significantly higher SES than AA participants in CHAP, and the average SES level of the sample as a whole was higher than the national average. As such, given that socioeconomic diversity was central to the HANDLS study design, the present study may have greater representation of lower SES White participants than previous studies in this area. This may partly explain why the present findings suggest relatively poorer trajectories in standing balance and right-handgrip strength for White participants compared their AA counterparts.

Notably, there is increasing recognition that lower SES Whites are at increased risk for morbidity and mortality in midlife (Case & Deaton, 2015). Case and Deaton (2017) reported that although midlife mortality rates continue to fall for nearly all other racial/ethnic groups in the United States, these rates have actually increased for Whites with only a high school degree or less. For example, in 1999, the mortality rate for non-Hispanic Whites aged 50-54 years with only a high school degree was 30% lower than for AAs of the same age group overall (i.e., across education levels); by 2015, a complete reversal had occurred, such that mortality for Whites with only a high school degree was 30% higher. According to the authors, this increase in mortality has been paralleled by self-reported declines in health, mental health, and ADLs and with concurrent increases in chronic pain, inability to work, and deteriorations in liver function among Whites with only a high school education or less (Case & Deaton, 2017).

These prior findings may inform the present study's findings, which demonstrated greater age-related balance and handgrip strength decline among Whites than their AA counterparts during midlife. Many of the same health factors that have contributed to the morbidity-mortality increase among lower SES Whites over the last two decades may also negatively influence physical performance and functional status. These factors include tobacco use (e.g., Rapuri, Gallagher, & Smith, 2007), inappropriate or elevated medication use (Gnjidic et al., 2012; Landi et al., 2007), chronic pain (Weiner, Rudy, Morrow, Slaboda, & Lieber, 2006), and poor mental health (Penninx et al., 2000; Yanagita et al., 2006). Additionally, at lower levels of SES (or across SES levels), Whites (versus AAs) may also have fewer resilience factors that have been shown to relate to physical functioning or self-reported disability, such as social support (Unger et al., 1999) and ADL-specific self-efficacy (de Leon, Seeman, Baker, Richardson, & Tinetti, 1996), although to my knowledge this has yet to be examined. The present study adjusted for poverty status and literacy (two markers of SES), but future research should seek to examine interactions among race, SES, and age with single-leg balance performance to determine whether SES-related factors are contributing to the unexpected racial patterns observed in the present study. In that regard, previous researchers (e.g., Williams, Mohammed, Leavell, & Collins, 2010) have urged examination of interactions between race and SES in health disparities research, given that examination of their respective main effects alone might produce misleading findings. Lastly, future studies should consider a range of SES indicators, such as educational attainment, neighborhood residence, and wealth, which might each uniquely influence cognitive and physical function trajectories and may have effects that vary as a function of race.

Relatedly, the present racial disparities in right handgrip strength and standing balance might be explained, at least in part, by racial differences in occupational status. Past research has shown that AAs participate in low-status, low-wage occupations at higher rates than their White counterparts (Grodsky & Pager, 2001). Such occupations are more likely to be physically demanding (Krueger & Burgard, 2011), and therefore may confer musculoskeletal benefits in some cases (Haas et al., 2012). However, the relation between occupational status and health is highly complex, and indeed lower-status workers are also more likely to work in dirty or dangerous conditions (Krueger & Burgard, 2011). For example, in a cross-sectional study of White, AA, and Hispanic-American adults who were 51 to 80 years of age, Haas and colleagues (2012) demonstrated that only *skilled* manual occupations (i.e., higher-status) conferred benefits for handgrip strength over professional/managerial and other non-manual occupations after adjustment for age, sex, race/ethnicity, nativity, parental education, childhood health, and adult

SES. Conversely, *unskilled* manual occupations (i.e., lower status) were not associated with improved physical performance or lung function in that study - rather, the authors concluded that any musculoskeletal benefit gained by working in an unskilled manual occupation may have attenuated due to greater risk for chronic diseases among this population (Haas et al., 2012). Indeed, prior studies have shown that physically demanding occupations are associated with knee osteoarthritis (Toivanen et al. 2009), and that lower-status occupations increase exposure to dust and other particles that adversely influence lung function (Krueger & Burgard, 2011). Additionally, it is possible that lower education and income among workers in unskilled manual occupations would attenuate any benefit of physically demanding work to musculoskeletal health among unskilled manual workers.

Nonetheless, it is possible that working in a manual occupation, whether skilled or unskilled, confers some health and functional benefits during midlife, prior to the onset of age-related diseases, arthritis, and/or chronic pain. Therefore, if AAs had higher participation in manual occupations than Whites in the present study (which was not examined herein), this might partly explain their slower age-related physical decline in handgrip strength and balance domains. Conversely, if non-skilled manual occupations are associated with health problems across the lifespan (including during midlife), then it is possible that Whites in the present study had higher participation in such occupations (again, this was not examined herein). Future studies should examine how self-reported race relates to occupational status, and whether this confers differential risks and/or benefits to physical function at different periods in the adult lifespan.

The present analyses also yielded a significant main effect of race with left-handgrip strength that was not explicitly hypothesized, such that AAs had stronger left grips than their

Whites counterparts. As discussed in detail above (see discussion of right hand grip strength), this is consistent with prior cross-sectional research demonstrating that AAs have stronger handgrips than their White counterparts, but is inconsistent with research demonstrating that AAs have higher rates of frailty.

Sex x Age.

Lastly, hypothesis 1 posited that female sex would be associated with greater age-related decline in physical performance across domains. Results did not confirm this hypothesis. Findings revealed non-significant interactions of sex and age for handgrip strength and balance tasks, in addition to a significant interaction of sex and age with lower extremity strength and endurance that was not in the hypothesized direction. That is, men demonstrated greater age-related decline in lower extremity strength and endurance than women. Most prior research does not provide support for these findings. For instance, prior studies have shown that women perform more poorly on measures of physical function and experience greater decline in physical functioning over time than men (Ferrucci et al., 2000; Penninx et al., 2000; Seino et al., 2014; Fredericksen et al., 2006; Cooper et al., 2014). Additionally, these findings are inconsistent with prior studies that have shown that older women have higher rates of self-reported disability than older men. (Guralnik et al., 1994; Merrill et al., 1997; Kennedy et al., 2002). However, the present sex-related differences in lower extremity strength and endurance decline are indeed consistent with findings from Botoseneanu and colleagues (2013), which examined sex-related trajectories in physical decline after adjusting for mortality bias. After adjustment for mortality effects, Botoseneanu and colleagues (2013) found that older men (versus older women) demonstrated greater age-related decline in lower extremity function over time. Furthermore, another study by the same research group demonstrated that despite having faster accumulation of self-reported disability, older women experienced slower decline in physical performance over 13.5 years than older men after adjustment for length-of-survival and other sociodemographic and health factors (Botoseneanu et al., 2016). Although the present study did not statistically address mortality effects, the use of a relatively younger sample (i.e., middle-aged adults between 30 to 64 years at baseline), with lower age-related mortality risk than older samples used in prior studies, may have unintentionally accomplished this goal. This finding emphasizes the importance of considering mortality effects in longitudinal studies of physical functioning and why it is crucial to assess decline in functional abilities prior to older adulthood.

Additionally, as discussed, occupational status may differentially influence physical performance across the adult lifespan, such that participation in manual occupations might confer musculoskeletal benefits during middle adulthood, but greater risk for physical decline during older adulthood after onset of age-related chronic diseases and musculoskeletal pain. Notably, according to the Bureau of Labor Statistics (2017), men (versus women) are more likely to work in natural resources, construction, and maintenance occupations (95.3% male; 4.7% female) and production, transportation, and material moving occupations (78.9% male; 22.1% female). It is plausible that higher male participation in such physically demanding jobs contributed to better physical performance across time points among men in the present study, as well as better lower-extremity function among men at younger ages (see Figure 7). However, if participation in certain manual occupations increases risk for age-related chronic diseases, pain-related disorders (e.g., knee osteoarthritis), and poorer lung function in older adulthood (Haas et al., 2012), this could partly explain why men experienced greater *decline* in lower extremity strength and endurance from younger to older ages than women in the present study (see Figure 7). Indeed, future studies should examine how different occupational patterns among men and women contributed to the present study's findings.

The present analyses also yielded several significant main effects of sex that were not nested beneath significant interactions (and that were not explicitly hypothesized). Findings revealed that men (versus women) had greater left- and right-handgrip strength performance and were less likely to fail the single-leg balance task across time points. These main effects of sex are consistent with the overwhelming consensus in the physical performance literature (e.g., Nicolay & Walker, 2005). Furthermore, whereas men demonstrated greater decline in lower extremity strength and endurance than women, no other sex differences in rates of decline were observed for other outcomes in this study. Rather, sex differences for other outcomes appear to remain stable over time during middle adulthood. It is possible that sex differences in rates of physical performance decline become more profound in other domains at later periods in the adult lifespan.

Hypothesis 2: Race x Sex x Age.

The second hypothesis predicted that AA women would experience greater decline in physical performance over time than White women and men of both races. Results did not support this hypothesis. This finding is inconsistent with prior literature showing that racial disparities in disability and poor physical functioning are larger among women than men, such that AA women have higher disability scores and perform most poorly in key aspects of physical performance than other groups, with the exception of handgrip strength (de Leon et al., 2005; Fuller-Thomson et al., 2009). Furthermore, a traditional intersectionality framework suggests that AA women would be at greater risk for poor health outcomes than other groups, largely due to the synergistic effects of gender- and race-related social disadvantage (i.e., double jeopardy) (e.g., Cummings & Jackson, 2008). The current lack of significant findings may be due, in part to characteristics of the present sample that included a relatively younger age range and greater racial and socioeconomic diversity as compared to prior research. In addition, given the relatively younger age range of the present sample, analyses may have been underpowered (i.e., too few participants in a given racial-sex group) to detect relatively smaller decline in physical functioning during midlife. Additionally, the present analyses adjusted for two indicators of SES (i.e., poverty status and literacy), whereas other studies of sociodemographic variation in physical performance typically adjusted for only one SES indicator (e.g., Botoseneau et al., 2016), used education instead of literacy (e.g., Seeman et al., 1994), or used a composite variable for SES (e.g., de Leon et al., 2005). As such, the present study's unique adjustment for both poverty status and literacy might have partly contributed to the null findings for hypothesis 2. However, at least one prior study found that racial disparities in physical functioning persisted after adjustment for SES, particularly among women (de Leon et al., 2005).

Hypothesis 3: EF x Race x Age and EF x Sex x Age.

The third hypothesis predicted that AAs and women with lower EF would demonstrate greater decline in physical performance over time than those with greater EF. Results did not support this hypothesis. I will discuss each component of this unsupported hypothesis in detail below, as well as significant three-way interaction effects that were not hypothesized.

EF x Race x Age.

Hypothesis 3 posited that AAs with lower EF would demonstrate greater age-related decline in physical performance than those with greater EF. Results did not confirm this hypothesis. Rather, findings revealed no significant interaction effects of EF, race, and age with single-leg balance, lower extremity strength and endurance, and left-handgrip strength. The three-way interaction hypotheses were largely exploratory; however, as discussed above, these null findings are inconsistent with prior studies indicating that EF are implicated in the planning and execution of movement (Mirabella et al., 2014), as well as well-documented racial disparities in physical performance (e.g., de Leon et al., 2005).

Nonetheless, results revealed a significant three-way interaction of EF, race, and age with right-handgrip strength, such that, age-related trajectories of decline in right-handgrip strength diverged as a function of EF among Whites, but converged as a function of EF among AAs. Although Whites had similar levels of performance at younger ages irrespective of EF, those with lower EF displayed greater age-related decline over time. However, whereas the performance of AAs varied as a function of EF at younger ages, performance converged over time; indeed, higher levels of EF were associated with greater decline among AAs, and AAs with lower EF demonstrated negligible change in this outcome between Waves 1 and 3. That is, despite having the lowest initial levels of right-handgrip strength, performance was roughly stable over time in this group. Furthermore, when contrasting racial groups, it is apparent that AAs and Whites with greater EF demonstrated similar trajectories of decline in right-handgrip strength over time; conversely, Whites with lower EF demonstrated greater decline in right-handgrip strength than AAs with lower EF. To my knowledge, this particular three-way interaction has never been examined before with regard to handgrip strength or other physical performance outcomes. Additionally, as discussed, to my knowledge there have been no previous longitudinal studies of racial differences in handgrip strength decline over time. The findings in Whites find more support in prior studies, which have demonstrated that greater EF is associated with better upper limb motor function (e.g., Hayashi et al., 2016) (however, these studies have not considered the role of race in such associations). Therefore, it is unclear why, in the present study, lower EF differentially predicted right-handgrip strength decline in AA and White middle-aged adults.

One potential explanation for the present findings might lie in racial disparities in muscle mass. As discussed, cross-sectional studies have found that AAs have stronger grips than Whites (Kurina et al., 2004; Rantanen et al., 1994; Newman et al., 2003), which might be related to greater muscle mass in AA individuals. Although beyond the scope of the present study, it is possible that AAs with lower EF, while having lower right-handgrip strength at younger ages, are less susceptible to EF-related decline in handgrip strength over time than lower-EF Whites due to a buffering effect of greater muscle mass. Indeed, racial differences in handgrip strength have been shown to attenuate with adjustment for muscle mass (Newman et al., 2003). Future studies examining racial and cognitive determinants of handgrip strength should adjust or examine the role of muscle mass in these associations.

Other explanatory factors might include racial differences in lifestyle factors (e.g., tobacco use) in the present study's sample, which have previously been shown to attenuate racial differences in handgrip strength (Newman et al., 2003). Furthermore, another prior study demonstrated that, among men, racial disparities in handgrip strength are only present at higher levels of SES. These previous cross-sectional findings suggest that racial differences in handgrip strength are highly complex, and examination of these associations compels the consideration of moderating factors. As such, future research should examine additional factors that might elucidate potential moderators such as the synergistic effects of race and SES (Williams et al., 2010) in addition to possible explanatory mechanisms such as racial and socioeconomic disparities in chronic disease (Kington & Smith, 1997).

As discussed above, underlying WM pathology is associated with both poor EF and physical performance, including handgrip strength performance (Sachdev et al., 2005). Past research has demonstrated that AAs have greater numbers of severe WML than Whites (Liao et al., 1997), and that among first-degree relatives of adults with early-onset coronary disease, AAs had greater deep WML than their White counterparts (Nyquist et al., 2014). Combined with the present study's findings, past neuroimaging studies suggest that race-related disparities in handgrip strength might be at least partially explained by differences in neurobiological aging, particularly declining WM status. Further, as described above, the SMA is associated with EF and voluntary motor control (Nachev, Kennar, & Husain, 2008). Additionally, the SMA is implicated in handgrip strength and complex finger movements that require fine-motor control (Ward & Franconia, 2003; Shibaski, 1993), suggesting that SMA status may also be contributing to the present findings.

Unlike handgrip strength, EF did not predict age-related change in lower extremity strength and endurance or single-leg balance over time; however, as described above, EF was associated with lower average levels of performance in these domains independent of age. These differences in findings for upper versus lower extremity strength and endurance may be explained, at least in part, by the differential motor skills required for handgrip strength tasks, which require fine-motor coordination, compared to the lower extremity strength and balance tasks. Indeed, previous studies have suggested a relation between motor task complexity and the degree to which EF are required for physical performance. For example, Muir-Hunter and colleagues (2014) reported that associations of EF and balance were strongest with more complex balance tasks, primarily because of variation in cognitive demands. In addition, studies have reported slower performance when participants are asked to perform a second task while walking, suggesting that EF are recruited to assist with more complex physical tasks (Yogev-Seligmann et al., 2008). As such, it is possible that, in the present study, performance on handgrip strength tasks was more susceptible to changes in EF over a five-year period because they require fine-motor coordination. Conversely, the Ten Times Sit-to-Stand and single-leg balance tasks may not have warranted activation of EF to the same degree, making these tasks less susceptible to mild changes in EF during middle adulthood. Task complexity may be an important consideration when using EF measures to screen adults at risk for functional decline (Liu-Ambrose et al., 2007).

Although results did not reveal a significant three-way interaction among EF, race, and age with left-handgrip strength, findings trended toward significance in the same direction (p's $<$ .10 for the fully adjusted and reduced models; see Results). Although statistical analyses for grip strength outcomes adjusted for dominant handedness, these discordant findings might be attributed to low representation of left-handed participants in the study sample. Additionally, there was slightly greater variability in left-handgrip strength (ranged from 4 to 95, SD = 12.2) than in right-handgrip strength (ranged from 5 to 83, SD = 11.4), which might have made detecting a statistically significant effect more difficult. Furthermore, results of the three-way interaction trended toward significance, which suggests that findings might have achieved statistical significance if analyses had greater statistical power. Alternatively, future studies might consider examining the average strength between hands.

EF x Sex x Age

Hypothesis 3 posited that women with lower EF would demonstrate greater age-related decline in physical performance than those with greater EF. Results did not confirm this hypothesis. Rather, findings revealed no significant interactions of EF, sex, and age with respect to single-leg balance, lower extremity strength and endurance, and right- and left-handgrip strength. Although this hypothesis was considered exploratory, lack of confirmation is generally inconsistent with prior literature indicating that EF is associated with physical functioning (Mirabella et al., 2014) and functional status (Royall et al., 2007), and the presence of sex differences in physical performance and age-related physical decline (Ferrucci et al., 2000?; Penninx et al., 2000; Seino et al., 2014; Fredericksen et al., 2006; Cooper et al., 2014). Furthermore, as mentioned, these findings are inconsistent with well-documented sex disparities in self-reported age-related physical disability (Guralnik et al., 1994; Merrill et al., 1997; Kennedy et al., 2002). Nonetheless, the null EF, sex, and age interaction may indicate that participants' sex indeed does not moderate associations between EF in age-related physical performance decline when such associations exist, regardless of the physical domain being measured (at least not during middle age).

Hypothesis 4: EF x Race x Sex x Age.

The fourth hypothesis predicted that AA women with lower EF would experience steeper decline in physical performance over time than all other groups. Results did not support the fourth hypothesis, nor did they reveal a significant four-way interaction effect of EF, race, sex, and age with physical performance outcomes. As described above, the null interaction effect is inconsistent with a traditional intersectionality framework that suggests that AA women are more likely to experience poorer health outcomes due to synergistic effects of gender- and race-related social disadvantage (e.g., Cummings & Jackson, 2008). The four-way interaction hypothesis was intended to be exploratory, given that other published studies have never examined this particular research question. It is possible that fourth-order effects among EF, race, sex, and age do not significantly relate to physical performance decline above and beyond the multitude of significant lower-order interactions and main effects previously described. It is also possible that our analyses were lacking the necessary power to detect fourth-order interaction effects of this nature, and that analysis with a larger sample might have produced significant results.

Covariate Effects.

Lastly, the present findings demonstrated several significant covariate effects. First, lower BMI was associated with lower right- and left-handgrip strength across time points. Overall, previous literature on the association between BMI and grip strength has demonstrated inconsistent findings, possibly due to highly variable sample demographics across studies (e.g., Schoffman et al., 2017; Shen et al. 2015, Rantanen et al., 2000; Apovian et al., 2002; Massy-Westropp, Gill, Taylor, Bohannon, & Hill, 2001). Conversely, the literature consistently suggests that greater BMI is related to poorer lower body function (Schoffman et al., 2017; Shen et al., 2015; Davis, Ross, Preston, Nevitt, & Wasnich, 1998). Future research should seek to understand why BMI is differentially associated with various aspects of physical functioning, as well as the role of BMI as a potential mediator of sociodemographic differences in physical performance, namely handgrip strength.

Next, living in poverty was associated with poorer right- and left-handgrip strength and lower extremity extremity strength and endurance across time points, and lower literacy was associated with poorer right- and left-handgrip strength and single-leg balance across time points. These trends suggest that lower SES, as indicated by poverty status and literacy scores, confers risk for poor physical functioning across domains. As discussed, future research should examine interactions between indicators of SES, race, sex, and EF to further understand their independent and synergistic effects as related to physical performance outcomes.

Finally, being left-handed was associated with greater left-handgrip strength and lower right-handgrip strength. These findings are consistent with previously published literature and published norms (e.g., Strauss et al., 2006).

Study Limitations.

The current study has several limitations. First and foremost, the non-normality of the tandem stand balance outcome and strong underrepresentation of participants who failed to pass that particular task did not allow for analysis of tandem stand balance performance. Given that tandem balance is a less complex task than single-leg balance, it might have been helpful to compare whether differences in balance task complexity related to differential patterns of performance. However, the relatively low difficulty of tandem stand balance task suggests that it might be an inappropriate measure to assess balance function during middle adulthood. Likewise, the lack of convergence in the hierarchically constructed models for single-leg balance required the removal of BMI and poverty status from those analyses. Although literacy was retained to adjust for SES, future studies should examine whether the significant findings found for single-leg balance are attenuated when fully adjusting for all relevant covariates.

Second, the EF composite score does not allow for specific examination of different EF-subdomains. EF comprise a multi-dimensional cognitive domain involved in the orchestration of other cognitive functions for the purposes of goal-directed behavior. Individual EF tests measure different executive domains and it may be useful to parse apart the aspects of EF that are implicated in physical performance changes over time. However, the literature suggests that the association between EF and physical performance outcomes may reflect common underlying neurobiological substrates (e.g., WM status), and it was therefore deemed useful to utilize an inclusive EF composite score of several interrelated domains for the purposes of this study.

Third, the present study limited its examination of cognitive domains to those under the EF umbrella. This restricted scope is a limitation of the present study, because changes in other cognitive domains might also contribute to age-related physical performance decline. However, the present study chose to examine the EF because a vast literature supports for their role physical performance and functional status (see Parihar et al., 2013; Yogev-Seligmann et al., 2008; Royall et al., 2007).

Fourth, the physical performance assessment in HANDLS is limited and does not include a measure of gait speed, which is the physical performance domain most widely studied in this research area. This perhaps limits the applicability of the present findings to the existing physical performance literature. However, the present study did utilize diverse and reliable measures of key physical performance domains that are crucial for healthy aging, and thereby makes a unique contribution to the literature.

Fifth, this study only included data from two time points approximately five years apart. This is a limitation of the present study because increasing the number of measurement time points would elucidate long-term trends in physical performance outcomes. In addition, increasing the number of time points might allow for the examination of non-linear trends in physical performance decline. To my knowledge, however, this was one of the first studies to examine associations between EF and physical functioning at more than one time point, thus representing a unique contribution to the literature.

Sixth, this study did not examine how poverty status, literacy, or other SES indicators (e.g., occupational status) interact with EF, race, or sex to predict age-related physical function decline. Although the present study adjusted for poverty status and literacy (i.e., two indicators of SES), interactive relations of SES with other independent variables may influence physical performance outcomes. Indeed, examination of how poverty status, literacy, and/or occupational status interact with EF and sociodemographic factors may have elucidated a clearer understanding of findings observed in the present study.

Finally, the uneven samples across time points and specific analyses is a limitation of the present study. Although linear mixed-effects regression has advantages over more traditional longitudinal data analytic strategies with regard to missing data, it is possible that patterns of missing data influenced the present study's findings. Additionally, due to how the data were collected, it was not possible to determine with certainty why some participants were missing particular data points.

Study Strengths.

This study contributed uniquely to the literature in several ways. First, this study was the first to elucidate interactive relations among EF, race, and sex with age-related physical performance decline. In particular, prior to this study, there has been a paucity of research examining longitudinal decline in physical performance over time as a function of EF. The use of linear and logistic mixed-effects regression for longitudinal analyses was also a strength, given clear advantages of these statistical techniques over alternative, more traditional methods such as rmANOVA. In addition, the unique diversity of the HANDLS sample expanded on past research in this area by including a diverse sample of participants who were AA and White, men and women, and living above and below the poverty level. The findings suggest that a lifespan perspective that considers individual differences in EF, as well as individuals' race and sex, is critical when studying age-related decline in physical functioning. Most importantly, the present study offers further justification for neuroimaging studies that can elucidate the neurobiological underpinnings of concurrent EF and physical performance decline, as well as sociodemographic variation in physical function trajectories.

Suggestions for Future Research.

The present study offers several directions for future research. First, future studies should consider how other individual differences variables, such as SES, might interact with EF, race, and sex to influence physical function. In particular, future studies should consider the role of occupational status (i.e., skilled versus unskilled; manual versus non-manual) in physical function during middle and older adulthood, and further consider how this explains or relates to sociodemographic patterns in physical function across the lifespan. Additionally, future studies should consider how other social determinants unique to participants in the present study, such as the urban environment and specific neighborhood characteristics, may have contributed to the lack of hypothesis confirmation as well as discrepancies with previously published studies. Indeed, the present findings may be predicated, at least in part, on unique characteristics of Baltimore City, relative to those of other urban, suburban, or rural communities. Second, researchers should examine the roles of various EF subdomains in physical performance decline, which might further elucidate putative mechanisms. Third, future data analyses should consider modeling EF as a random effect in order to assess longitudinal covariation between EF and physical performance. Fourth, future studies should examine whether baseline age contributed to the findings in the present study and whether individuals in different age cohorts experience differential patterns of physical performance decline as a function of EF, race, and sex. Fifth, the present study and previous literature warrant examination of neurobiological underpinnings of EF-physical performance associations, particularly WM, SMC, PFC, and basal ganglia status. Sixth, it will be important to consider the roles of other cognitive domains in age-related physical performance decline, such as global cognition, learning and memory, visual-spatial processing, and information processing speed. Seventh, future studies should investigate the interplay among cognition, race, and sex concerning other physical performance and functional domains, such as gait speed and ADLs, respectively. Eighth, subsequent studies should expand on this work by analyzing longer-term trends in cognitive and physical performance decline, measured at several time points throughout the adult lifespan. Finally, given the present effects of BMI, poverty status, and literacy, future studies should seek to examine how these variables moderate or mediate associations between EF, sociodemographic factors, and physical performance decline.

Study Implications.

The present study has several potential public health and clinical implications. First, the present study demonstrates that performance on relatively brief tests of EF and physical functioning is highly related, which may be useful information for practitioners aiming to screen individuals at risk for age-related cognitive or physical disability. Next, the present findings demonstrated sociodemographic variation in different domains of physical performance over time that were not supported by prior literature. In doing so, the patterns demonstrated in the present study challenge the consensus that women and AAs are greater risk for physical disability than men and Whites, respectively. Rather, during middle age, the present findings suggest that men and Whites may be more vulnerable to decline in key aspects of physical functioning. Because the present study's sample was younger than those used in most prior studies, these results may indicate early signs of emerging physical disability. As discussed in the introduction, objective measures of physical performance are early clinical indicators of health and functional decline and therefore may be amenable to intervention. Taken together, the present study may inform early screening and intervention strategies that target individuals at heightened risk for future physical decline, namely those with lower EF, men, and Whites.

Conclusions.

Consistent with existing literature, the present findings demonstrated that EF relates to levels of physical performance across domains during middle adulthood, such that greater EF is associated with greater physical functioning. Conversely, inconsistent with the proposed hypotheses and prior literature, the present study demonstrated that, during middle age, EF does not predict age-related decline in standing balance, lower extremity strength and endurance, or left-handgrip strength. Furthermore, this was this first study to demonstrate that EF differentially relates to age-related decline in right-handgrip strength as a function of race, such that age-related trajectories of decline in right-handgrip strength diverged over time as a function of EF among Whites, but converged as a function of EF among AAs. The present findings also challenged the general consensus in the literature that, overall, AAs and women experience faster physical performance decline in most domains. Rather, the present findings suggest that, during middle age, women experience lesser decline in lower extremity strength and endurance than men, AAs experience lesser decline in standing balance and right-handgrip strength than their White counterparts, and other sex and racial disparities in physical performance decline are not present. To the extent that objective measures of physical performance relate to future disability, the present findings suggest that long-term trajectories in physical functioning may favor women and AAs.

As discussed, future research should examine whether potential explanatory mechanisms reviewed in the discussion section mediate the findings that emerged in this study. Future research is necessary to determine whether EF mediates associations between neurobiological differences and aspects of physical functioning (versus neurobiological differences acting as a third variable), particularly handgrip strength, standing balance tasks, and lower extremity strength and endurance. In addition, future neuroimaging studies might elucidate why EF is implicated in physical decline only in particular performance domains. Neuroimaging studies will be critical for understanding the neurobiological underpinnings of EF-physical performance relations, as well as their sociodemographic variation in age-related physical decline. Finally, future research should extend the length of study and increase the number of measurement points, which will increase statistical power and shed further light on long-term trajectories in physical performance decline.

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Table 1

Participant Characteristics Stratified by Sex and Self-Identified Race and in the Overall Sample

(a) Participant characteristics at Wave 1

	AA Women (n = 461)[a]	AA Men (*n* = 322)[a]	White Women (*n* = 321)[a]	White Men (*n* = 218)[a]	Overall Sample (*N* = 13
Age (years)	48.29(±9.33)	48.27(±8.82)	48.86(±8.96)	48.59(±8.42)	48.48(±8.
Poverty status (%<125% 2004 federal poverty level)	46.0%	42.5%	35.2%	29.8%	39.
Literacy (WRAT-3 total score)	40.91(±6.95)	41.08(±8.22)	45.53(±6.76)	44.56(±8.42)	42.68(±7.
BMI	31.63(±8.41)	27.51(±5.71)	30.67(±8.11)	29.15(±6.42)	29.99(±7.
BTA	6.24(±2.16)	6.29(±2.13)	7.4(±2.07)	6.87(±1.98)	6.64(±2.
DSF	6.83(±2.10)	7.25(±2.19)	7.52(±2.28)	7.63(±2.45)	7.23(±2.
DSB	5.15(±2.02)	5.20(±2.03)	6.30(±2.36)	6.11(±2.47)	5.60(±2.
TMT-B (time to completion)	176.21(±174.14)	172.57(±169.39)	103.66(±121.25)	120.27(±138.68)	148.48(±159.
Verbal fluency	17.51(±4.72)	19.02(±5.46)	20.09(±5.68)	20.20(±5.92)	18.95(±5.
EF composite (summed z-scores)	-0.49(±2.17)	-0.02(±2.27)	0.86(±2.62)	0.69(±2.64)	0.15(±2.
Right-handgrip strength[b]	28.60(±7.34)	42.71(±10.09)	27.29(±6.36)	41.70(±9.52)	33.91(±10.
Left-handgrip strength[c]	29.08(±7.31)	44.54(±10.45)	26.98(±6.73)	43.25(±9.89)	34.71(±11.
Single-leg stand (% failed)[d]	21.1%	10.5%	10.6%	14.1%	14.
Ten Times Sit-to-Stand[e]	33.20(±8.98)	35.30(±9.87)	33.91(±7.60)	33.44(±8.70)	34.11(±8.
Dominant hand[f] (% left-handed)[f]	9.0%	13.5%	11.2%	11.0%	11.
Dominant hand[f] (% ambidextrous)	1.9%	4.4%	3.1%	6.4%	3.

[a] Sample size at Wave 1 except where noted otherwise below.
[b] Sample sizes for right-handgrip strength: AA women (*n* = 312); AA men (*n* = 226); White women (*n* = 248); White men (*n* = 164); Overall sample (954)
[c] Sample sizes for left-handgrip strength: AA women (*n* = 309); AA men (*n* = 226); White women (*n* = 248); White men (*n* = 168); Overall sample (*n* 951)
[d] Sample sizes for single-leg balance stand: AA women (*n* = 218); AA men (*n* = 190); White women (*n* = 170); White men (*n* = 128); Overall sample = 706)
[e] Sample sizes for Ten Times Sit-to-Stand: AA women (*n* = 216); AA men (*n* = 291); White women (*n* = 221); White men (*n* = 158); Overall sample (= 886)
[f] Sample sizes for dominant handedness: AA women (*n* = 322); AA men (*n* = 229); White women (*n* = 258); White men (*n* = 172); Overall sample (*n* 981)

(b) Participant characteristics at Wave 3

	AA Women (*n* = 497)	AA Men (341)	White Women (*n* = 345)	White Men (*n* = 232)	Overall Sample (*N* = 14
Age (years)	52.78(±9.23)	52.79(±8.82)	53.39(±9.02)	53.05(±8.60)	52.98(±8.
Poverty status (%<125% 2004 federal poverty level)	43.7%	39.0%	33.3%	29.7%	37.
Literacy (WRAT-3 total score)	41.10(±6.89)	41.36(±8.15)	45.14(±7.41)	44.69(±8.33)	42.74(±7.
BMI	32.35(±8.66)	27.91(±5.96)	31.16(±7.87)	29.83(±7.18)	30.58(±7.
BTA	6.15(±2.16)	6.02(±2.22)	6.99(±2.07)	6.72(±2.17)	6.42(±2.
DSF	6.94(±2.02)	7.04(±2.21)	7.68(±2.31)	7.73(±2.35)	7.27(±2.
DSB	5.22(±1.96)	5.12(±1.98)	6.19(±2.25)	6.07(±2.21)	5.57(±2.
TMT-B (time to completion)	186.12(±184.91)	176.89(±170.44)	113.97(±126.08)	129.94(±149.10)	157.09(±165.
Verbal fluency	17.70(±4.70)	19.31(±5.27)	20.09(±5.76)	20.75(±6.10)	19.17(±5.
EF composite (z-score)	-0.36(±2.19)	-0.19(±2.33)	0.75(2.62)	0.81(±2.58)	0.14(±2.
Right-handgrip strength[b]	28.91(±7.08)	45.55(±10.24)	27.49(±6.65)	44.06(±10.39)	35.03(±11.
Left-handgrip strength[c]	29.32(±7.79)	47.32(±11.06)	27.99(±7.24)	45.50(±10.95)	35.97(±12.

Single-leg stand (% failed)[d]	33.2%	22.4%	36.7%	26.4%	29.
Ten Times Sit-to-Stand[e]	34.48(±7.55)	32.93(±7.34)	34.59(±7.65)	33.10(±7.08)	33.89(±7.
Dominant hand[f] (% left-handed)[f]	12.3%	10.1%	9.8%	13.5%	11.
Dominant hand[f] (% ambidextrous)	5.0%	2.4%	1.5%	4.5%	3.

[a] Sample size for Wave 3 variables except where noted otherwise below.

[b] Sample sizes for right-handgrip strength: AA women (n = 461); AA men (n = 311); White women (n = 318); White men (n = 216); Overall sample (1306)

[c] Sample sizes for left-handgrip strength: AA women (n = 459); AA men (n = 311); White women (n = 314); White men (n = 213); Overall sample (n 1297)

[d] Sample sizes for single-leg balance stand: AA women (n = 265); AA men (n = 232); White women (n = 196); White men (n = 159); Overall sample = 852)

[e] Sample sizes for Ten Times Sit-to-Stand: AA women (n = 395); AA men (n = 285); White women (n = 276); White men (n = 193); Overall sample (= 1149)

[f] Sample sizes for dominant handedness: AA women (n = 467); AA men (n = 317); White women (n = 328); White men (n = 222); Overall sample (n 1334)

Table 2

Analysis-specific Sample Sizes According to Dependent Variables of Interest

Dependent variable	*n* at Wave 1	*n* at Wave 3	Total no. of observations	Valid *n* across waves
Right-handgrip strength	954	1,306	2,260	1,489
Left-handgrip strength	951	1,297	2,248	1,485
Single-leg standing balance	706	852	1,558	1,112
Ten times sit-to-stand	886	1,149	2,035	1,372

Table 3

Participant Characteristics Stratified by Age at Waves 1 and 3

(a) Participant characteristics at Wave 1

	< 48.47 years (n = 645)[a]	≥ 48.47 years (*n* = 677)[a]
Poverty status (%<125% 2004 federal poverty level)	43.9%**	36.0%**
Sex (% women)	60.0%	58.3%
Race (% African American)	62.3%*	56.3%*
Literacy (WRAT-3 total score)	42.59(±7.87)	42.76(±7.66)
BMI	29.49(±7.78)*	30.46(±7.42)*
BTA	6.71(±2.09)	6.58(±2.22)
DSF	7.35(±2.25)	7.12(±2.24)
DSB	5.68(±2.29)	5.52(±2.20)
TMT-B (time to completion)	132.05(±148.13)***	164.13(±167.32)***
Verbal fluency	19.49(±5.59)***	18.43(±5.30)***
EF composite (summed z-scores)	0.26(±2.53)	0.04(±2.37)
Right-handgrip strength[b]	35.26(±10.56)***	32.61(±10.59)***
Left-handgrip strength[c]	36.64(±11.95)***	32.85(±10.89)***
Single-leg stand (% failed)[d]	11.4%**	18.5%**
Ten Times Sit-to-Stand[e]	32.92(±8.48)***	35.37(±39.29)***
Dominant hand[f] (% left-handed)[f]	13.6%**	8.5%**
Dominant hand[f] (% ambidextrous)[f]	3.1%	4.0%

Note. * : p < .05, ** : p < .01, *** : p < .001

[a] Sample size at Wave 1 except where noted otherwise below.

[b] Sample sizes for right-handgrip strength: < 48.47 years (*n* = 469); ≥ 48.47 years (*n* = 485)

[c] Sample sizes for left-handgrip strength: < 48.47 years (*n* = 467); ≥ 48.47 years (*n* = 484)

[d] Sample sizes for single-leg balance stand: < 48.47 years (*n* = 404); ≥ 48.47 years (*n* = 484)

[e] Sample sizes for Ten Times Sit-to-Stand: < 48.47 years (*n* = 455); ≥ 48.47 years (*n* = 431)

[f] Sample sizes for dominant handedness: < 48.47 years (*n* = 484); ≥ 48.47 years (*n* = 497)

(b) Participant characteristics at Wave 3

	< 52.98 years (n = 695)[a]	≥ 52.98 years (*n* = 720)[a]

Poverty status (%<125% 2004 federal poverty level)	40.3%	35.3%
Sex (% women)	59.7%	59.3%
Race (% African American)	60.0%	58.5%
Literacy (WRAT-3 total score)	42.77(±7.85)	42.70(±7.76)
BMI	30.64(±8.27)	30.52(±7.40)
BTA	6.58(±2.14)**	6.26(±2.23)**
DSF	7.55(±2.30)***	7.00(±2.10)***
DSB	5.75(±2.19)**	5.40(±2.06)**
TMT-B (time to completion)	130.67(±148.04)***	182.59(±177.46)***
Verbal fluency	19.65(±5.80)**	18.72(±5.10)**
EF composite (summed z-scores)	0.33(±2.57)**	0.05(±2.32)**
Right-handgrip strength[b]	37.20(±12.41)***	32.85(±10.62)***
Left-handgrip strength[c]	38.50(±13.18) ***	33.44(±11.55)***
Single-leg stand (% failed)[d]	23.6%***	39.2%***
Ten Times Sit-to-Stand[e]	32.98(±8.18) ***	36.51(±9.99)***
Dominant hand[f] (% left-handed)[f]	12.6%*	7.9%*
Dominant hand[f] (% ambidextrous)[f]	3.5%	3.7%

Note. * : p < .05, ** : p < .01, *** : p < .001

[a] Sample size at Wave 1 except where noted otherwise below.

[b] Sample sizes for right-handgrip strength: < 48.47 years (*n* = 655); ≥ 48.47 years (*n* = 651)

[c] Sample sizes for left-handgrip strength: < 48.47 years (*n* = 649); ≥ 48.47 years (*n* = 648)

[d] Sample sizes for single-leg balance stand: < 48.47 years (*n* = 513); ≥ 48.47 years (*n* = 339)

[e] Sample sizes for Ten Times Sit-to-Stand: < 48.47 years (*n* = 603); ≥ 48.47 years (*n* = 283)

[f] Sample sizes for dominant handedness: < 48.47 years (*n* = 653); ≥ 48.47 years (*n* = 328)

Table 4

Matrix for Correlation Coefficients (Pearson's r) for All Variables from Waves 1 and 3

Variables	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
1. W1[a] right-handgrip strength	1.0																			
2. W3[b] right-handgrip strength	.78***	1.0																		
3. W1 left-handgrip	.88***	.77***	1.0																	
4. W3 left-handgrip	.75***	.90***	.81***	1.0																
5. W1 10 chair stands	-.19***	-.20***	-.21***	-.17***	1.0															
6. W3 10 chair stands	-.17***	-.22***	-.19***	-.22***	.45***	1.0														
7. W1 single-leg balance (pass/fail)	-.11**	-.10*	-.12**	-.09*	.06	.002	1.0													
8. W3 single-leg balance (pass/fail)	-.136**	-.16***	-.16***	.17***	.12*	.16***	.17***	1.0												
9. W1 EF composite	.09**	.15***	.09**	.14***	-.09*	-.16***	-.05	-.10*	1.0											
10. W3 EF composite	.11**	.15***	.12***	.14***	-.06	-.13***	-.09*	-.16***	.71***	1.0										
11. W1 BMI	-.10**	-.10**	-.12***	-.12***	.07*	.05	.17***	.20***	-.05	-.04	1.0									
12. W3 BMI	-.07*	-.07*	-.09*	-.09**	.04	.03	.15***	.21***	-.06*	-.03	.91***	1.0								
13. Sex	.64***	.70***	.67***	.69***	-.08*	-.10**	-.06	-.12**	.04	.03	-.20***	-.20***	1.0							
14. Race	.06	.06*	.09**	.06*	.04	-.01	.06	-.04	-.22***	-.21***	-.01	-.01	.004	1.0						
15. Poverty status	-.06	-.10***	-.07*	-.08***	.09*	.07*	.01	.05	-.17***	-.18***	-.04	-.04	-.03	.11***	1.0					
16. Literacy	.02	.09**	.03	.08**	-.06	-.09**	-.03	-.12***	.49***	.473	.001	-.001	-.01	-.25***	-.25***	1.0				
17. W1 Left[c]	.002	.08**	.11**	.08*	-.05	-.03	-.02	-.03	-.003	.001	-.08*	-.09*	.04	-.004	-.004	-.04	1.0			
18. W3 Left[c]	-.01	.002	.08*	.08**	-.03	-.002	-.04	-.01	-.02	-.02	-.05	-.04	.05	-.01	-.01	-.05	.81***	1.0		
19. W1 Ambidextrous[d]	.02	.05	.04	.04	-.06	-.03	.02	-.04	.03	.01	.003	.02	.08*	-.04	-.04	-.003	-.07*	.05	1.0	
20. W3 Ambidextrous[d]	.08*	.07*	.08*	.09**	.01	-.05	-.05	.03	-.01	.01	-.02	.01	.08**	.02	.02	-.01	.02	-.06*	.28***	

Note. **p* < .05; ***p* < .01; ****p* < .001

[a] W1 = Wave 1

[b] W3 = Wave 3

[c] Dummy-coded dominant hand variable: Left-handed

[d] Dummy-coded dominant hand variable: Ambidextrous

Table 5

Beta-values from Hierarchically Constructed Linear Mixed-effects Regression Analyses for Right-handgrip Strength

	Model 1	Model 2	Model 3	Model 4
BMI	0.09***	0.09**	0.08**	0.08**
Poverty status	-1.41***	-1.38**	-1.37**	-1.36**
WRAT total score	0.05	0.05	0.05	0.05
Left [a]	-1.17*	-1.19*	-1.18*	-1.15*
Ambidextrous [b]	-0.40	-0.45	-0.39	-0.40
Age	-0.18***	-0.22***	-0.23***	-0.22***
EF	0.37***	0.27*	0.24	0.26
Race	2.09***	1.84**	1.79***	1.806**
Sex	15.9***	15.59***	15.65***	10.57***
Age×EF		-0.01	0.02	0.01
Age×Race		0.09*	0.08	0.08
Age×Sex		-0.04	-0.07	-0.08
EF×Race		0.02	0.03	0.03
EF×Sex		0.20	0.20	0.19
Race×Sex		0.32	0.19	0.11
Age×EF×Race			-0.04**	-0.03
Age×EF×Sex			-0.01	0.01
Age×Race×Sex			0.06	0.07
EF×Race×Sex			0.02	0.03
Age×EF×Race×Sex				-0.03

Note. * : p < .05, ** : p < .01, *** : p < .001
[a] Dummy-coded dominant hand variable: Left-handed
[b] Dummy-coded dominant hand variable: Ambidextrous

Table 6

Final Linear Mixed-effects Regression Model Estimating the 3-way Interaction Effect of EF × Race × Age with Change in Right-handgrip Strength between Waves 1 and 3

Model predictors	Unstandardized *B*	*SE*	*t*	*p*-value
Sex***	15.78	.40	39.55	<.001
BMI**	0.09	.03	3.51	.001
Poverty status**	-1.36	.41	-3.30	.001
WRAT total score*	0.06	.03	1.97	.049
Left[a]*	-1.22	.58	-2.09	.037
Ambidextrous[b]	-0.39	.90	-0.44	.661
EF**	0.34	.11	2.98	.003
Race***	1.88	.41	4.59	<.001
Age***	-0.26	.03	-7.67	<.001
EF×Race	0.04	.15	0.29	.772
EF×Age	0.01	.01	1.21	.226
Race×Age*	0.11	.04	2.50	.013
EF×Race×Age*	-0.04	.02	-2.60	.010

Note. * : $p < .05$, ** : $p < .01$, *** : $p < .001$

[a] Dummy-coded dominant hand variable: Left-handed

[b] Dummy-coded dominant hand variable: Ambidextrous

Table 7

Beta-values from Hierarchically Constructed Linear Mixed-effects Regression Analyses for Left-handgrip Strength

	Model 1	Model 2	Model 3	Model 4
BMI	0.08**	0.08**	0.07**	0.07**
Poverty status	-1.42**	-1.41**	-1.42**	-1.42**
WRAT total score	0.08*	0.07*	0.07*	0.07*
Left [a]	2.33***	2.37***	2.36***	2.35***
Ambidextrous [b]	1.84	1.85*	1.87*	1.88*
Age	-0.21***	-0.22***	-0.23***	-0.23***
EF	0.35***	0.32*	0.31*	0.30*
Race	2.42***	2.31***	2.25***	2.25***
Sex	16.94***	16.84***	16.88***	16.86***
Age×EF		-0.002	0.01	0.01
Age×Race		0.05	0.06	0.06
Age×Sex		-0.05	-0.05	-0.04
EF×Race		-0.15	-0.18	-0.12
EF×Sex		0.24	-0.28	0.27
Race×Sex		0.17	0.13	0.15
Age×EF×Race			-0.03	-0.03
Age×EF×Sex			0.01	0.01
Age×Race×Sex			-0.002	-0.01
EF×Race×Sex			-0.04	-0.05
Age×EF×Race×Sex				0.01

Note. * : $p < .05$, ** : $p < .01$, *** : $p < .001$

[a] Dummy-coded dominant hand variable: Left-handed

[b] Dummy-coded dominant hand variable: Ambidextrous

Table 8

Final Linear Mixed-effects Regression Model estimating the Main Effects of Age, EF, Race, and Sex with Left-handgrip Strength.

Model predictors	Unstandardized *B*	*SE*	*t*	*p*-value
BMI**	0.08	.03	2.90	.004
Poverty status**	-1.42	.44	-3.24	.001
WRAT total score*	0.07	.03	2.35	.019
Left[a]***	2.33	.62	3.80	<.001
Ambidextrous[b]	1.84	.94	-2.09	.050
Age***	-0.21	.02	1.96	<.001
EF***	0.35	.09	4.14	<.001
Race***	2.42	.43	5.62	<.001
Sex***	16.94	.43	39.77	<.001

Note. * : $p < .05$, ** : $p < .01$, *** : $p < .001$

[a] Dummy-coded dominant hand variable: Left-handed

[b] Dummy-coded dominant hand variable: Ambidextrous

Table 9

Beta-values from Hierarchically Constructed Logistic Mixed-effects Regression Analyses for Single-leg Standing Balance

	Model 1 [a]	Model 2 [a]	Model 3 [a]	Model 4 [a]
BMI	0.09***	0.08***	0.09***	0.09***
Poverty Status	0.33*	0.30	0.34*	0.35*
WRAT total score	-0.02*	-0.03*	-0.02*	-0.02*
Age	0.08***	0.11***	0.11***	0.12***
EF	-0.09**	-0.12*	-0.14*	-0.14*
Race	-0.31*	-0.34	-0.36	-0.36
Sex	-0.47**	-0.60*	-0.63*	-0.60*
Age×EF		-0.002	-0.002	-0.01
Age×Race		-0.04*	-0.05	-0.05*
Age×Sex		0.01	0.1	-0.01
EF×Race		-0.004	0.2	0.02
EF×Sex		0.08	0.12	0.12
Race×Sex		0.13	0.17	0.11
Age×EF×Race			0.004	0.01
Age×EF×Sex			-0.01	0.01
Age×Race×Sex			0.01	0.03
EF×Race×Sex			-0.06	0.06
Age×EF×Race×Sex				-0.02

Note. * : p < .05, ** : p < .01, *** : p < .001
[a] Model did not converge. Results may be invalid.

Table 10

Final Logistic Mixed-effects Regression Model Estimating the Two-way Interaction Effect of Race × Age with Single-leg Standing Balance.

Model predictors [a]	Unstandardized *B*	*SE*	*z*	*p*-value
WRAT total score*	-0.02	.01	-1.99	.047
Sex***	-0.65	.15	-4.18	<.001
EF**	-0.11	.04	-3.09	.002
Race	-0.25	.16	-1.59	.111
Age***	0.10	.02	6.31	<.001
Age × Race*	-0.04	.02	-1.99	.047

Note. * : $p < .05$, ** : $p < .01$, *** : $p < .001$

[a] This final logistic mixed-effects regression model converged after removing non-significant interaction terms, centering continuous variables, and removing BMI and poverty status from the analysis. Results are considered valid.

Table 11

Beta-values from Hierarchically Constructed Logistic Mixed-effects Regression Analyses for the Ten Times Sit-to-Stand

	Model 1	Model 2	Model 3	Model 4
BMI	0.03	0.03	0.03	0.03
Poverty status	1.56***	1.60***	1.61***	1.62***
WRAT total score	-0.03	-0.03	-0.03	-0.03
Age	0.20***	-.18***	0.17***	0.17***
EF	-0.19*	-0.08	-0.04	-0.04
Race	-0.31	0.02	0.03	0.04
Sex	-1.33	-1.07	-1.07	-1.06
Age×EF		-0.01	0.001	-0.001
Age×Race		-0.04	-0.02	-0.02
Age×Sex		0.12**	0.16*	-0.15*
EF×Race		-0.16	-0.24	-0.24
EF×Sex		-0.03	-0.12	-0.12
Race×Sex		-0.55	-0.57	-0.59
Age×EF×Race			0.001	0.01
Age×EF×Sex			-0.02	-0.02
Age×Race×Sex			-0.05	-0.04
EF×Race×Sex			-0.18	-0.18
Age×EF×Race×Sex				-0.01

Note. * : $p < .05$, ** : $p < .01$, *** : $p < .001$

Table 12

Final Linear Mixed-effects Regression Model Estimating the Two-way Interaction Effect of Sex × Age with the Ten Times Sit-to-Stand

Model predictors	Unstandardized *B*	*SE*	*t*	*p*-value
BMI	0.03	.03	1.06	.288
Poverty status***	1.59	.42	3.81	<.001
WRAT total score	-0.03	.03	-0.90	.371
Race	-0.29	.41	-0.71	.480
EF	-0.18	.08	-2.12	.034
Sex	-1.40	.40	-3.53	<.001
Age	0.16	.03	5.94	<.001
Sex × Age	0.13	.12	2.96	.003

Note. * : p < .05, ** : p < .01, *** : p < .001

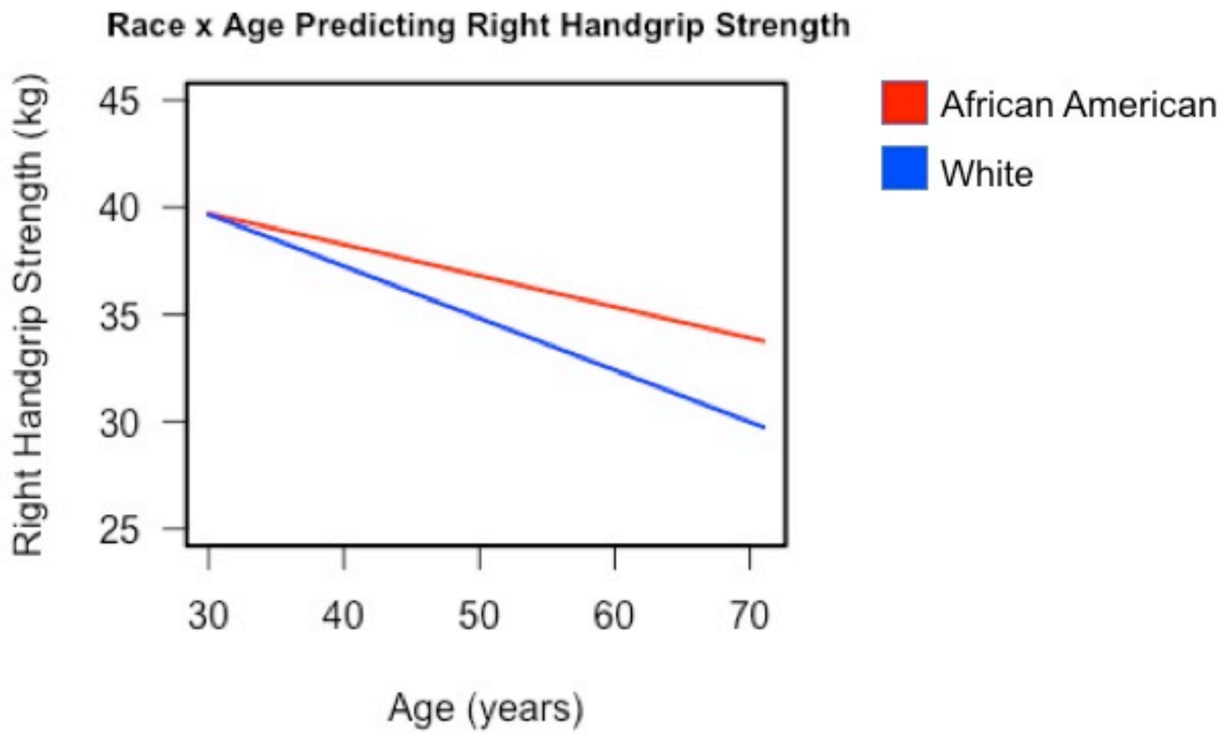

Figure 1. Race predicting age-related change in right-handgrip strength between Waves 1 and 3, such that Whites demonstrated greater age-related decline in right-handgrip strength than their AA counterparts.

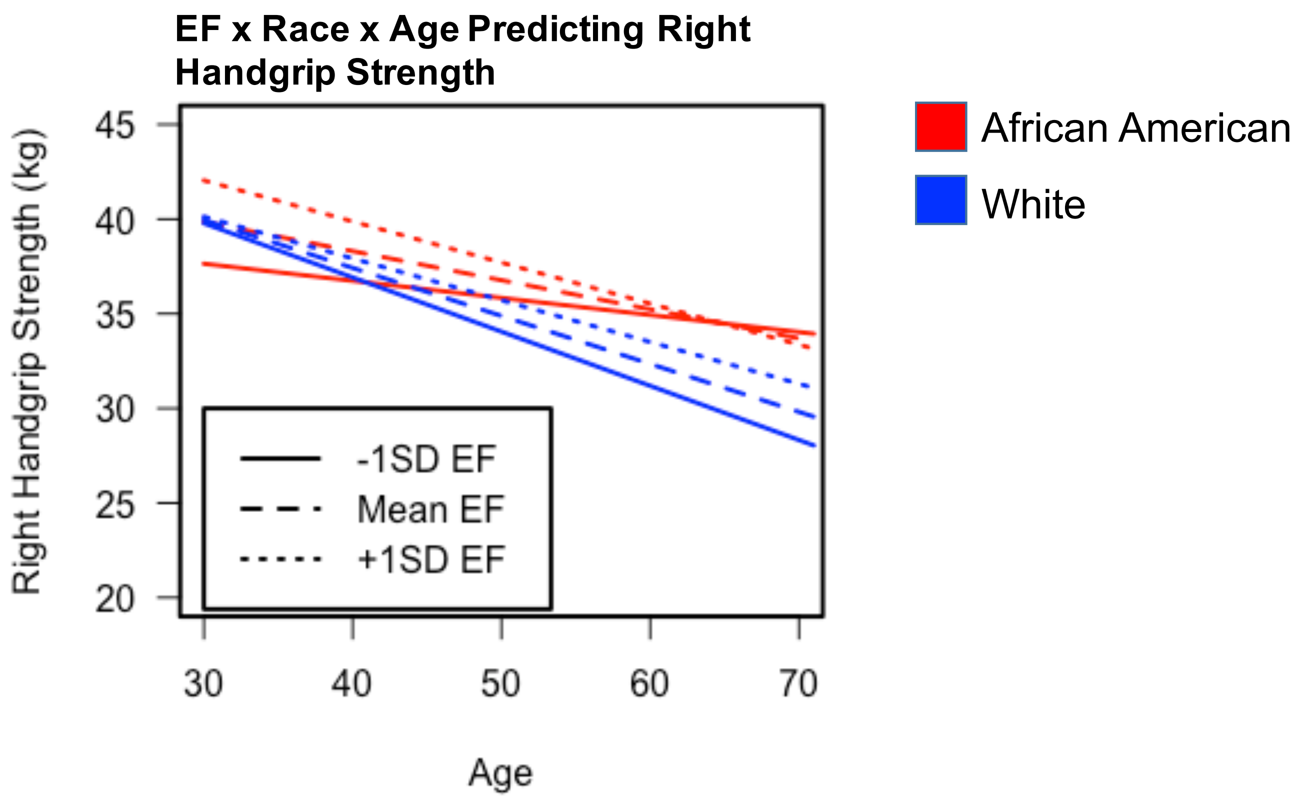

Figure 2. EF x race predicting age-related change in right-handgrip strength between Waves 1 and 3. Lower EF was significantly associated with greater decline in right-handgrip strength in Whites, but negligible decline in right-handgrip strength in AAs. Conversely, greater EF was associated with approximately equal rates of decline in Whites and AAs.

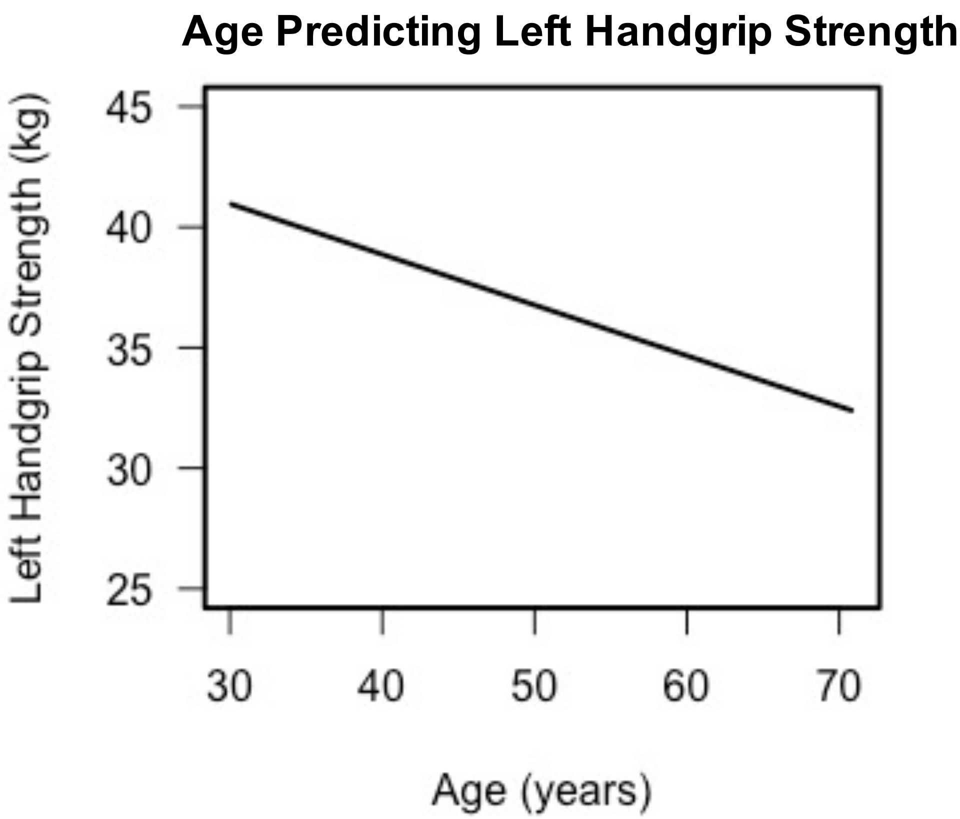

Figure 3. Age predicting change in left-handgrip strength performance between Waves 1 and 3, such that increased age was significantly associated with decline in left-handgrip strength.

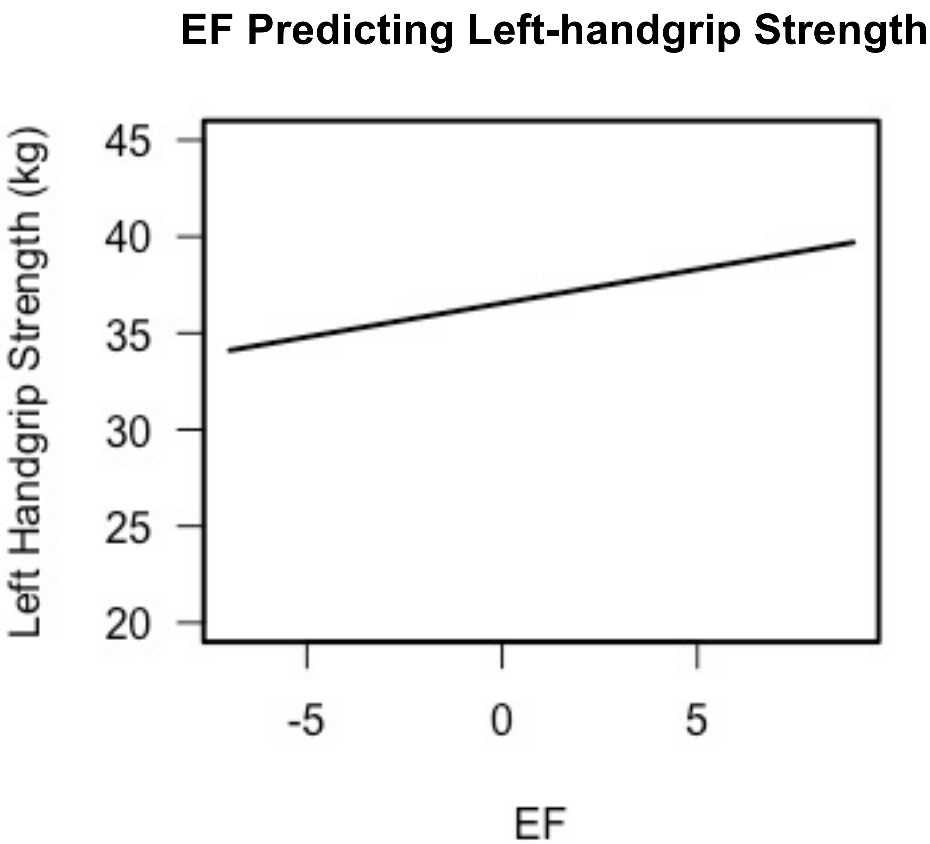

Figure 4. EF was significantly related to left-handgrip strength performance across time points, such that greater EF was associated with greater left-handgrip strength performance.

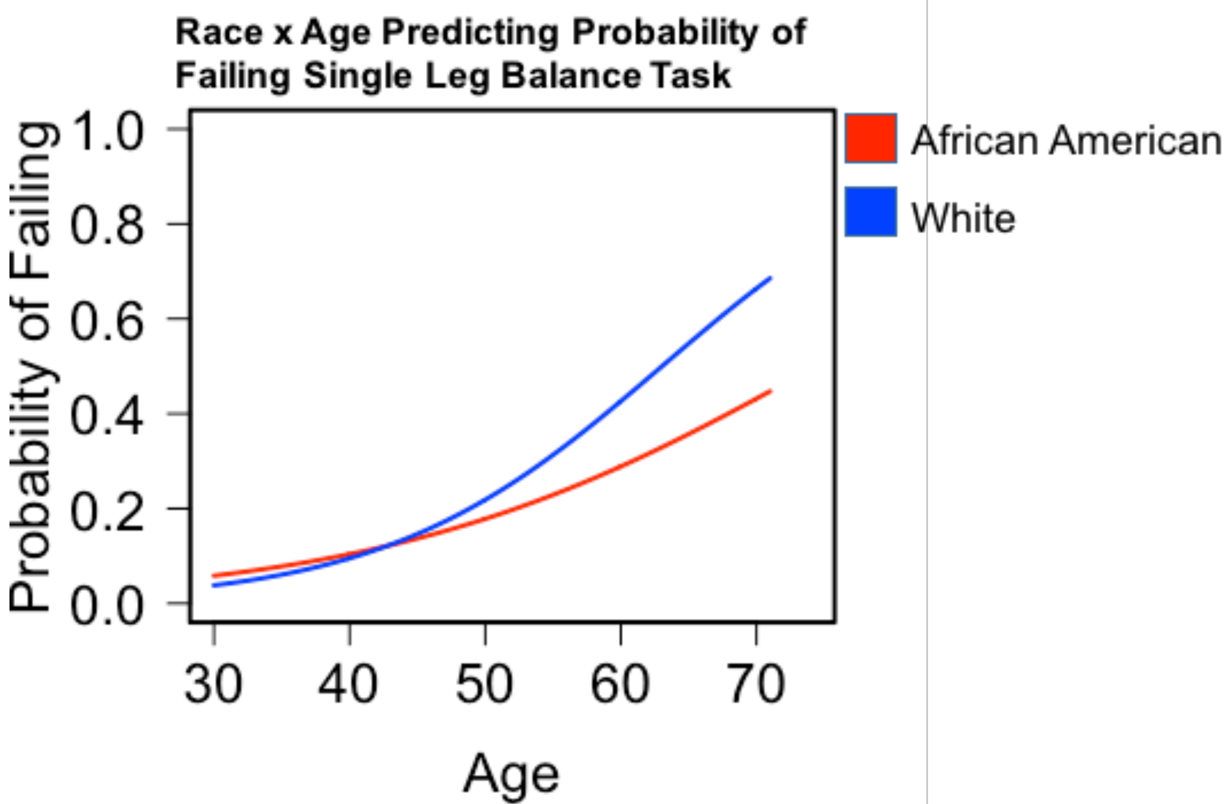

Figure 5. Race predicting age-related changes in probability of failing the single-leg balance task between Waves 1 and 3. White participants demonstrated greater age-related decline in single-leg balance than their AA counterparts, indicated by a greater increase in probability of failing the task with increased age.

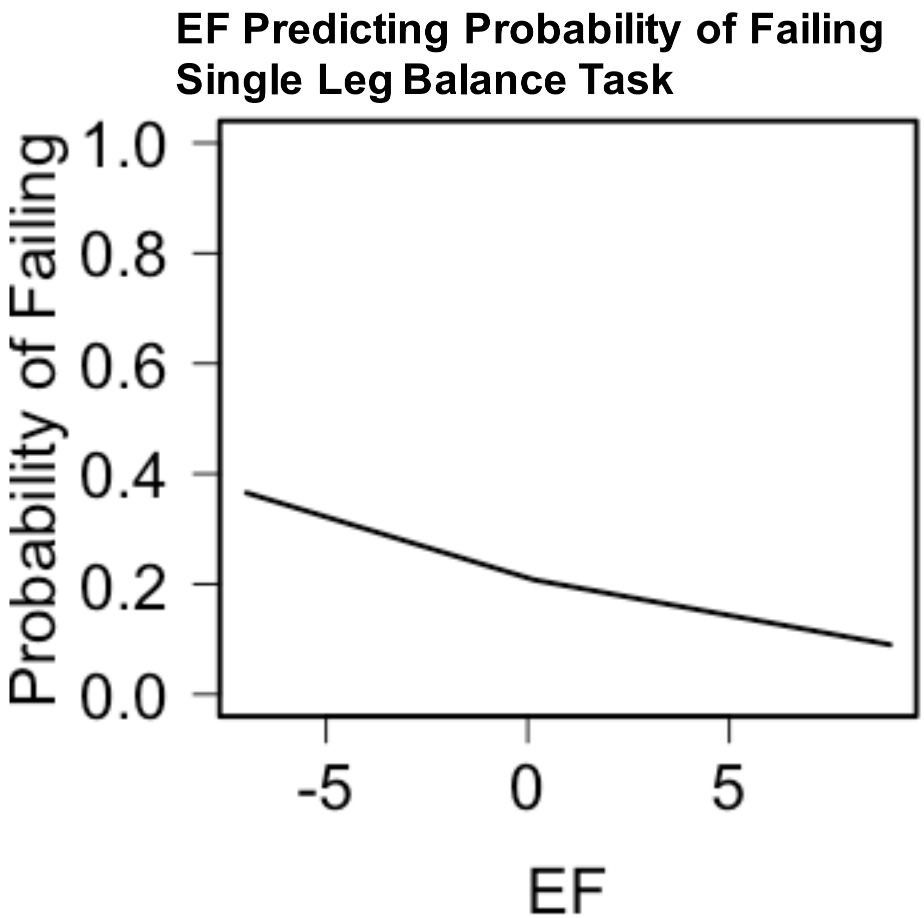

Figure 6. EF was significantly related to the probability of failing the single-leg balance task across time points, such that greater EF was associated with lower probability of failing the single-leg balance task.

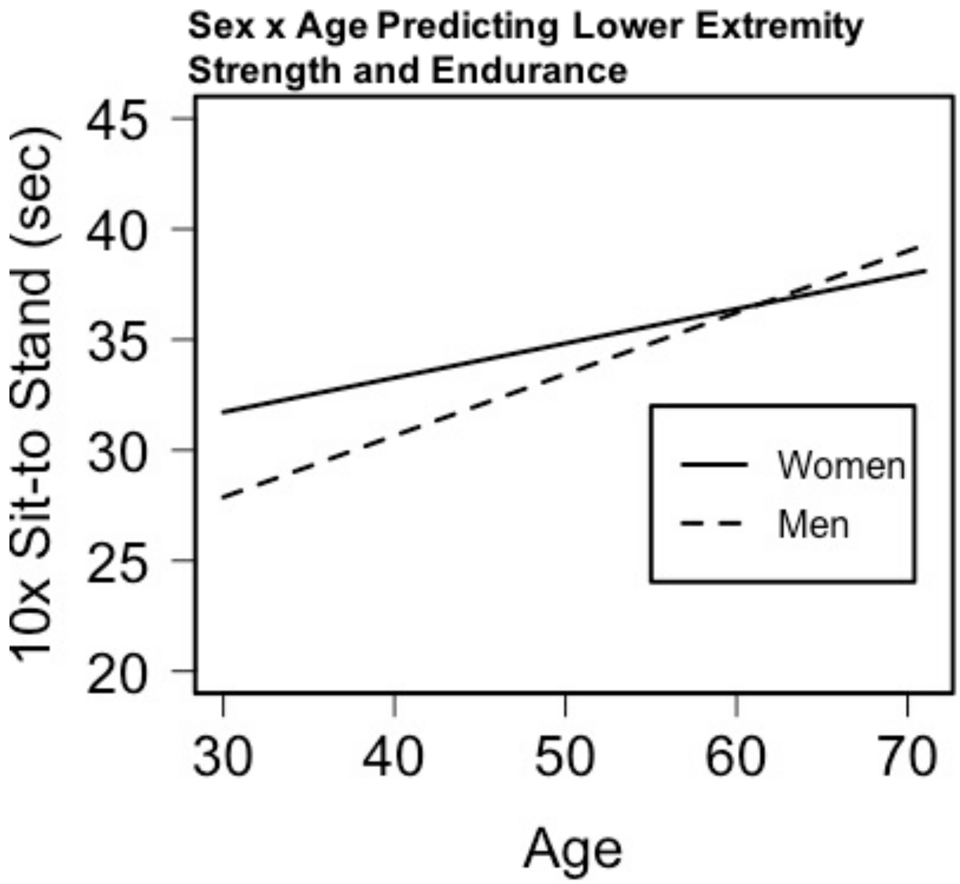

Figure 7. Sex predicting age-related change in performance on the Ten Times Sit-to-Stand between Waves 1 and 3. Men demonstrated greater slowing on the Ten Times Sit-to-Stand than women over time, indicating that men experienced greater age-related decline in lower extremity strength and endurance.

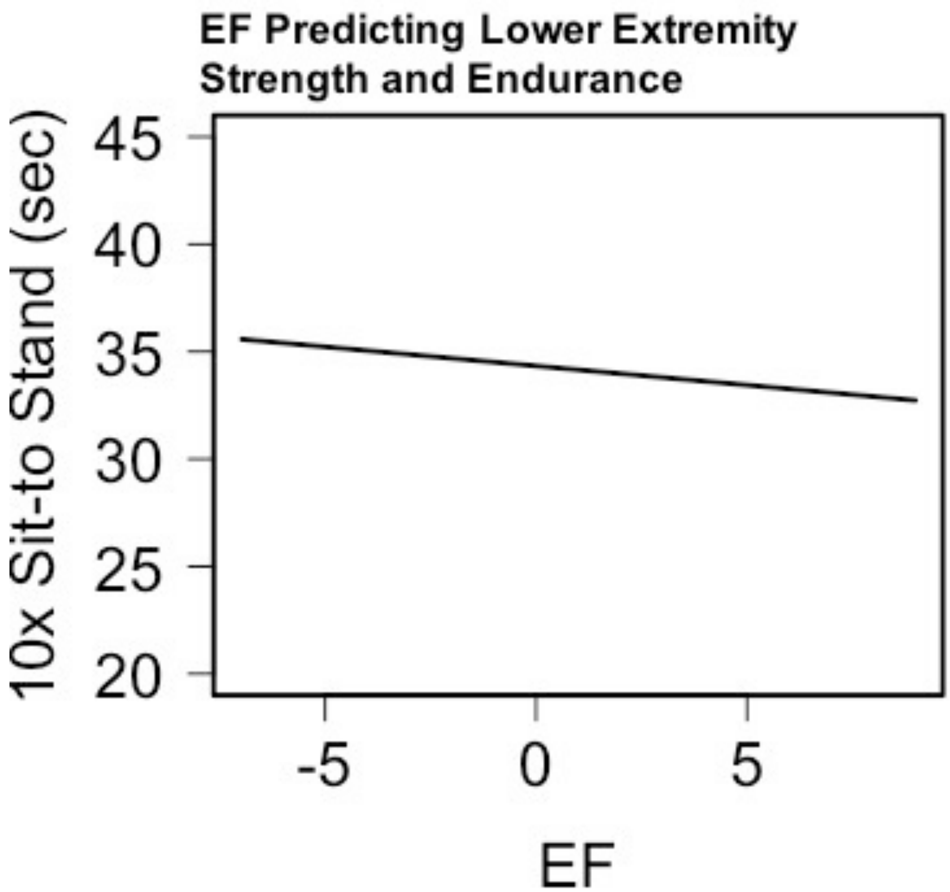

Figure 8. EF was significantly related to performance on the Ten Times Sit-to-Stand across time points, such that lower EF was associated with slower performance on the Ten Times Sit-to-Stand task across Waves 1 and 3.

Appendix

Acronym	Term
AA(s)	African American(s)
AD	Alzheimer's Disease
ADLs	Activities of Daily Living
ARWMC	Age-Related White Matter Changes
BMI	Body Mass Index
BTA	Brief Test of Attention
CHAP	Chicago Health and Aging Project
DSB	Digit Span Backward
DSF	Digit Span Forward
EF	Executive Functions
HANDLS	Healthy Aging in Neighborhoods of Diversity across the Life Span
IADLs	Instrumental Activities of Daily Living
MCI	Mild Cognitive Impairment
MMRV	Mobile Medical Research Vehicle(s)
PFC	Prefrontal Cortex
rmANOVA	Repeated-Measures Analysis-of-Variance
SES	Socioeconomic Status
SMA	Supplementary Motor Area
SMC	Supplementary Motor Cortex
TBI	Traumatic Brain Injury
TMT	Trail Making Test
TMT-A	Trail Making Test-Part A
TMT-B	Trail Making Test-Part B
WM	White Matter
WMH	White Matter Hyperintensities
WML	White Matter Lesions
WMSA	White Matter Signaling Abnormalities
WRAT-3	Wide Range Achievement Test-3