

## Striated muscle activator of Rho signalling (STARS) is reduced in ageing human skeletal muscle and targeted by miR-628-5p

A. P. Russell, M. A. Wallace, M. Kalanon, E. Zacharewicz, P. A. Della Gatta, A. Garnham and S. Lamon

Institute for Physical Activity and Nutrition (IPAN), School of Exercise and Nutrition Sciences, Deakin University, Geelong, Vic., Australia

Received 11 August 2016,  
revision requested 12 September 2016,  
revision received 10 October 2016,  
accepted 11 October 2016  
Correspondence: A. P. Russell,  
PhD, Institute for Physical Activity  
and Nutrition (IPAN), School of  
Exercise and Nutrition Sciences,  
Deakin University, Burwood, Vic.  
3125, Australia.  
E-mail: aaron.russell@deakin.edu.  
au

### Abstract

**Aim:** The striated muscle activator of Rho signalling (STARS) is a muscle-specific actin-binding protein. The STARS signalling pathway is activated by resistance exercise and is anticipated to play a role in signal mechanotransduction. Animal studies have reported a negative regulation of STARS signalling with age, but such regulation has not been investigated in humans.

**Methods:** Ten young (18–30 years) and 10 older (60–75 years) subjects completed an acute bout of resistance exercise. Gene and protein expression of members of the STARS signalling pathway and miRNA expression of a subset of miRNAs, predicted or known to target members of STARS signalling pathway, were measured in muscle biopsies collected pre-exercise and 2 h post-exercise.

**Results:** For the first time, we report a significant downregulation of the STARS protein in older subjects. However, there was no effect of age on the magnitude of STARS activation in response to an acute bout of exercise. Finally, we established that miR-628-5p, a miRNA regulated by age and exercise, binds to the STARS 3'UTR to directly downregulate its transcription.

**Conclusion:** This study describes for the first time the resistance exercise-induced regulation of STARS signalling in skeletal muscle from older humans and identifies a new miRNA involved in the transcriptional control of STARS.

**Keywords** ageing, exercise, microRNA, skeletal muscle, striated muscle activator of Rho signalling.

Ageing is characterized by a gradual increase in cellular damage and a decline in physical function over time. At the molecular level, multiple pathways are dysregulated with ageing, contributing to the arrest of cell growth and repair (Smith-Vikos & Slack 2012). In mammals, ageing is associated with a decline in skeletal muscle mass and function, referred to as sarcopaenia. It is estimated that human adults lose about 10% of their muscle mass by the age of 50, with a further average reduction of 1% per year until death

(Dorrens & Rennie 2003, Phillips 2012). Age-related muscle atrophy is linked to a disruption in skeletal muscle protein turnover (Boirie 2009) and reduced regenerative capacity (Brack & Rando 2007). In addition, the elderly demonstrate impaired phosphorylation of several key proteins involved in skeletal muscle protein synthesis following resistance exercise (Léger *et al.* 2008, Kumar *et al.* 2009, Zacharewicz *et al.* 2014). This phenomenon is referred to as anabolic resistance. Ageing is also associated with impaired

Notch, Wnt (Arthur & Cooley 2012) and myogenic regulatory factor (MRF) (Marsh *et al.* 1997, Dedkov *et al.* 2003) signalling. These pathways are important for efficient myogenesis (Corbu *et al.* 2010, Walker *et al.* 2012) and their downregulation is believed to contribute to inefficient muscle repair and function with age (Shadrach & Wagers 2011). The molecular mechanisms leading to age-related muscle wasting are complex, and our understanding is far from complete. Continued research is required to identify other signalling pathways that are important for the maintenance of muscle size and function and are perturbed in ageing human muscle.

The striated muscle activator of Rho signalling (STARS) protein is an actin-binding protein highly expressed in cardiac, smooth and skeletal muscle (Arai *et al.* 2002, Mahadeva *et al.* 2002, Peng *et al.* 2008, Troidl *et al.* 2009). STARS increases actin polymerization, resulting in the nuclear translocation of the serum response factor (SRF) transcriptional co-activator myocardin-related transcription factor-A (MRTF-A; also known as megakaryoblastic leukaemia 1 protein, MKL1) (Arai *et al.* 2002, Kuwahara *et al.* 2005). This signalling response enhances the activation of SRF gene transcription, which plays a role in maintaining skeletal muscle growth and repair (Olson & Nordheim 2010, Braun & Gautel 2011). STARS is also expressed in the nucleus (Troidl *et al.* 2009, Wallace *et al.* 2011) where it may interact directly with DNA to control gene transcription (Zaleska *et al.* 2015). *Stars* gene expression is decreased in skeletal muscle from aged mice (Sakuma *et al.* 2008) and pigs (Peng *et al.* 2008) when compared to young animals. The nuclear content of MRTF-A, but not total SRF, is lower in skeletal muscle of 24-month-old sarcopaenic mice when compared with 3-month-old mice (Sakuma *et al.* 2008). At present, it is unknown whether the STARS signalling pathway is downregulated in skeletal muscle of older compared with younger humans. Members of the STARS signalling pathway increase following a single bout of resistance exercise as well as training in young healthy subjects (Lamon *et al.* 2009), suggesting that they play a role in skeletal muscle adaptation and function. Molecular signalling responses to exercise are often attenuated in older when compared to younger muscle; however, whether this is the case for STARS signalling has not been investigated.

Striated muscle activator of Rho signalling is a transcriptional target of several transcription factors including MyoD,  $ERR\alpha$ , SRF and MEF2 (reviewed in Wallace *et al.* 2012). The recent identification of microRNAs (miRNAs) as additional regulators of gene expression has added another level of complexity in our understanding of transcriptional regulation. miRNAs are now considered as essential regulators of

skeletal muscle health (reviewed in Zacharewicz *et al.* 2013). In human skeletal muscle, exercise and age regulate miRNA expression (Zacharewicz *et al.* 2013, 2014). miRNAs mainly act by degrading specific mRNA species to prevent the resulting protein translation (Olsen & Ambros 1999, Lee *et al.* 2004b, Wightman *et al.* 2004, Humphreys *et al.* 2005, Pillai *et al.* 2005, Huili *et al.* 2010), and miRNA activity is largely dependent on its binding capacity to the target mRNA molecule (Brennecke *et al.* 2005, Hu & Bruno 2011). While it has been established that miR-9 (Buller *et al.* 2012), miR-133a (Liu *et al.* 2008), miR-150 (Liu *et al.* 2015), miR-200 (Buller *et al.* 2012), miR-320a (Chen *et al.* 2015) and miR-483-5p (Qiao *et al.* 2011) regulate SRF expression and miR-31 (Katsura *et al.* 2016) and miR-206 (Zhang *et al.* 2015) regulate MRTF-A expression, the miRNA regulation of STARS is unknown.

The aims of this study were to, firstly, measure the basal expression levels of STARS and members of its signalling pathway in skeletal muscle from young and older male subjects. Secondly, we compared the regulation of STARS and members of its signalling pathway in young and older human subjects following a single bout of resistance exercise. Thirdly, we used a high-throughput PCR-based miRNA array platform to determine whether there was an effect of age and exercise on the regulation of the miRNAs known to target SRF and MRTF-A. Finally, we combined bioinformatics prediction modelling with luciferase reporter technology to identify the potential miRNA regulation of STARS.

## Methods

### Subjects

The subject characteristics and methodology have been published previously (Stefanetti *et al.* 2014). Ten young (18–30) and 10 older (60–75) healthy males participated in the study. The study was approved by the Deakin University Human Research Committee (EC: 2011-043) in accordance to the *Declaration of Helsinki* (2013) (<http://www.wma.net/en/30publications/10policies/b3/>). Informed consent and inclusion and exclusion criteria have been described elsewhere (Stefanetti *et al.* 2014).

### Trial protocol

Dual-energy X-ray absorptiometry scan (DXA), preliminary testing, exercise protocol and muscle biopsy procedure have been described in the study by Stefanetti *et al.* (2014). Briefly, the subjects completed an acute bout of resistance exercise that consisted of

three sets of 14 repetitions of leg extension exercise at 60% of maximal voluntary contraction (1 RM). Muscle biopsies were collected immediately after exercise and 2 h later.

#### Protein extraction and western blotting

Total protein was extracted using RIPA buffer (Millipore, North Ryde, NSW, Australia) with 1  $\mu$ L/mL protease inhibitor cocktail (Sigma-Aldrich, Castle Hill, NSW, Australia) and 10  $\mu$ L/mL Halt Phosphatase Inhibitor Single-Use Cocktail (Thermo Scientific, Rockford, IL, USA). Total protein content was determined using the BCA Protein Assay Kit (Pierce Biotechnology, Rockford, IL, USA) according to the manufacturer's instructions. Electrophoresis was performed using a 4–12% NuPAGE<sup>®</sup> Novex Bis-Tris Gel (Life Technologies, Mulgrave, Vic., Australia) in NuPAGE<sup>®</sup> SDS MOPS Running Buffer (Life Technologies). Protein transfer was performed onto PVDF membrane in a Bjerrum buffer containing 50 mM Tris, 17 mM glycine and 10% methanol. The membranes were blocked with 5% BSA in PBS, after which they were incubated at 4 °C with the following primary antibodies diluted 1:1000 in 5% BSA in PBS: STARS (Institute of Medical and Veterinary Science, Adelaide, SA, Australia); SRF (sc-335; Santa Cruz, CA, USA); MRTF-A (sc-32909; Santa Cruz); phospho-SRF-S103 (ab53130; Abcam, Cambridge, MA, USA). Following overnight incubation, the membranes were washed and incubated for 1 h with a goat anti-rabbit IgG antibody labelled with an infrared-fluorescent 800 nm dye (Alexa Fluor<sup>®</sup> 800; Life Technologies) diluted 1:5000 in PBS containing 50% Odyssey<sup>®</sup> blocking buffer (LI-COR Biosciences, Lincoln, NE, USA) and 0.01% SDS. After washing, the proteins were exposed on an Odyssey<sup>®</sup> Infrared Imaging System (LI-COR Biosciences) and individual protein band optical densities were determined using the Odyssey<sup>®</sup> Infrared Imaging System software. All blots were normalized against the GAPDH protein (G8795; Sigma-Aldrich). C<sub>2</sub>C<sub>12</sub> myotubes overexpressing ADV-STARS (100 MOI) were used as a STARS-positive control (Wallace *et al.* 2016). C<sub>2</sub>C<sub>12</sub> myoblasts (~70% confluent) were treated for 1 h with phorbol ester 12-O-tetradecanoylphorbol-13-acetate (TPA), also known as 12 myristate 13-acetate. TPA stimulates the serum response element, providing a positive control for phosphorylated SRF (Gineitis & Treisman 2001).

#### RNA extraction and reverse transcription

RNA extraction and reverse transcription procedures have been described in the study by Stefanetti *et al.* (2014). miRNA reverse transcription has been described in the study by Zacharewicz *et al.* (2014).

#### Real-time PCR

Real-time PCR was carried out using a Stratagene MX3000 thermal cycler to measure mRNA levels. mRNA levels of STARS, SRF, MRTF-A and PPIA were measured using Brilliant<sup>®</sup> Multiplex QPCR Master Mix (Agilent Technologies, Santa Clara, CA, USA) and 5 ng of cDNA. Primer and probe details have been published previously (Lamon *et al.* 2009). The PCR conditions were 1 cycle of 10 min at 95 °C; 40 cycles of 30 s at 95 °C, 60 s at 60 °C. For PPIA, a melting curve was included at the end of the PCR cycles. To compensate for variations in input RNA amounts and efficiency of the reverse transcription, data were normalized to the PPIA (peptidylprolyl isomerase A, cyclophilin) gene. PPIA gene expression levels were stable and did not differ between age, time or a combination of both factors (Fig. S1). Ct values were obtained from the MxPro qPCR software (Agilent Technologies). Ct values were then logarithmically transformed and mean log-transformed Ct values (referred to as arbitrary unit [AU] values) were considered for further analysis.

#### miRNA arrays and statistical analysis

miRNA expression in the samples was assessed using the TaqMan<sup>®</sup> Array Human MicroRNA A+B Cards version Set v3.0 (Life Technologies) according to the manufacturer's instructions (Zacharewicz *et al.* 2014), and the data were normalized using the global normalization function. Statistical treatment of the data (split plot ANOVA) has been comprehensively described in the study by Zacharewicz *et al.* (2014).

#### Identification of miRNAs predicted to target the STARS signalling pathway

The miRNAs predicted to target STARS were predicted on the basis of 3'UTR sequence homology using miRWalk (Jin *et al.* 2009). The miRWalk software enables the prediction of miRNA targets by incorporating several known prediction software programs. miRanda, miRDB, miRWalk, RNA22 and Targetscan were chosen within the miRWalk program. A predicted mRNA/miRNA interaction was considered significant when identified by a minimum of four prediction software programs.

#### Luciferase reporter assay

HEK293 cells (ATCC, Manassas, VA, USA) ( $1\text{--}2 \times 10^5$ /mL) were seeded in black-walled 96-well plates. Twenty-four hours after seeding, cells were cotransfected with 150 ng pNanoglo2 vector

(Promega, Alexandria, NSW, Australia) containing either: no insertion (empty control); the full-length human *Stars* 3' UTR; the putative miR-628-5p STARS target site (including the predicted seed site with 10 base pairs on either side); or its mutant control (primers listed in Table S1), cloned between *SacI* and *NheI* downstream of the Nanoluc luciferase; together with 5 nM miR-628-5p mimics (mirVana™ miRNA mimic; Life technologies), or an irrelevant miRNA control (miR-99b-5p), using Lipofectamine 2000 (Life technologies) following the manufacturer's protocol. Four or 6 h post-transfection, the media was removed and replaced by normal media (DMEM with 10% FBS). Twenty-four hours later, cells were consecutively assayed for Firefly and Nanoluc luciferase expression using the Nano-Glo® Dual-luciferase® Reporter assay kit (Promega) following the manufacturer's protocol.

#### Statistical methods

All data are reported as mean  $\pm$  SEM. After normal distribution of the data and homogeneity of variance established, analysis of variance (ANOVA) was used to compare group means. *Post hoc* analysis was conducted where appropriate using the least significant difference (LSD) test. The significance levels were set at  $P < 0.05$ .

## Results

#### Subjects' demographics

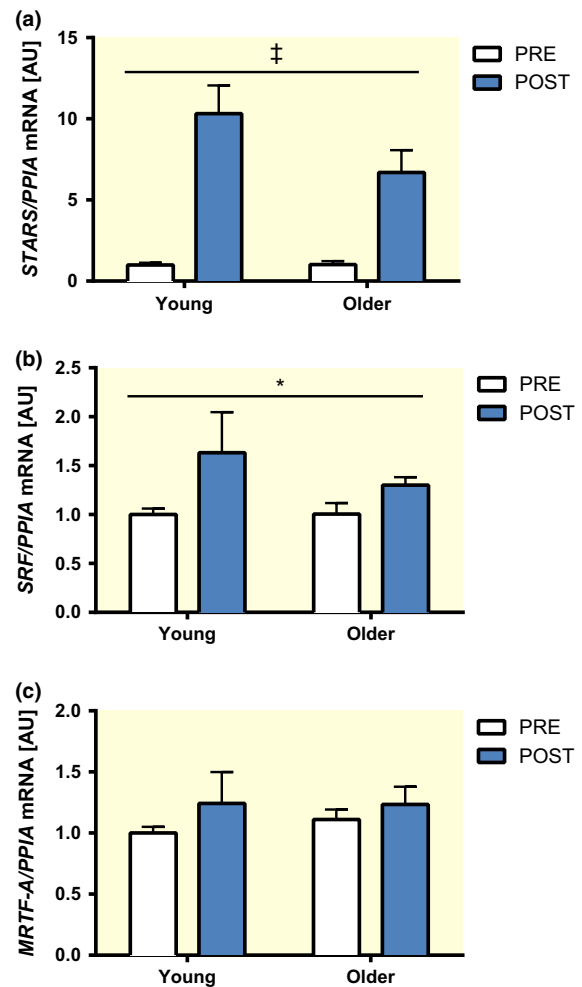
Subjects' physiological characteristics have been described elsewhere (Stefanetti *et al.* 2014).

#### Regulation of STARS, SRF and MRTF-A mRNA expression with exercise and ageing

Resistance exercise increased *STARS* mRNA expression in young (10.3-fold) and older (6.7-fold) subjects (main effect of exercise,  $P < 0.001$ ) (Fig. 1a). Similarly, *SRF* mRNA expression increased by 1.63-fold and 1.3-fold in young and older subjects respectively (main effect of exercise,  $P < 0.05$ ) (Fig. 1b). There was no significant age  $\times$  exercise interaction. *MRTF-A* mRNA levels did not vary with age or exercise (Fig. 1c).

#### Regulation of STARS, SRF and MRTF-A protein expression with exercise and ageing

Exercise had no effect on the protein levels of STARS, MRTF-A, SRF and phospho-SRF measured in young or older subjects 2 h post-exercise (Fig. 2). A

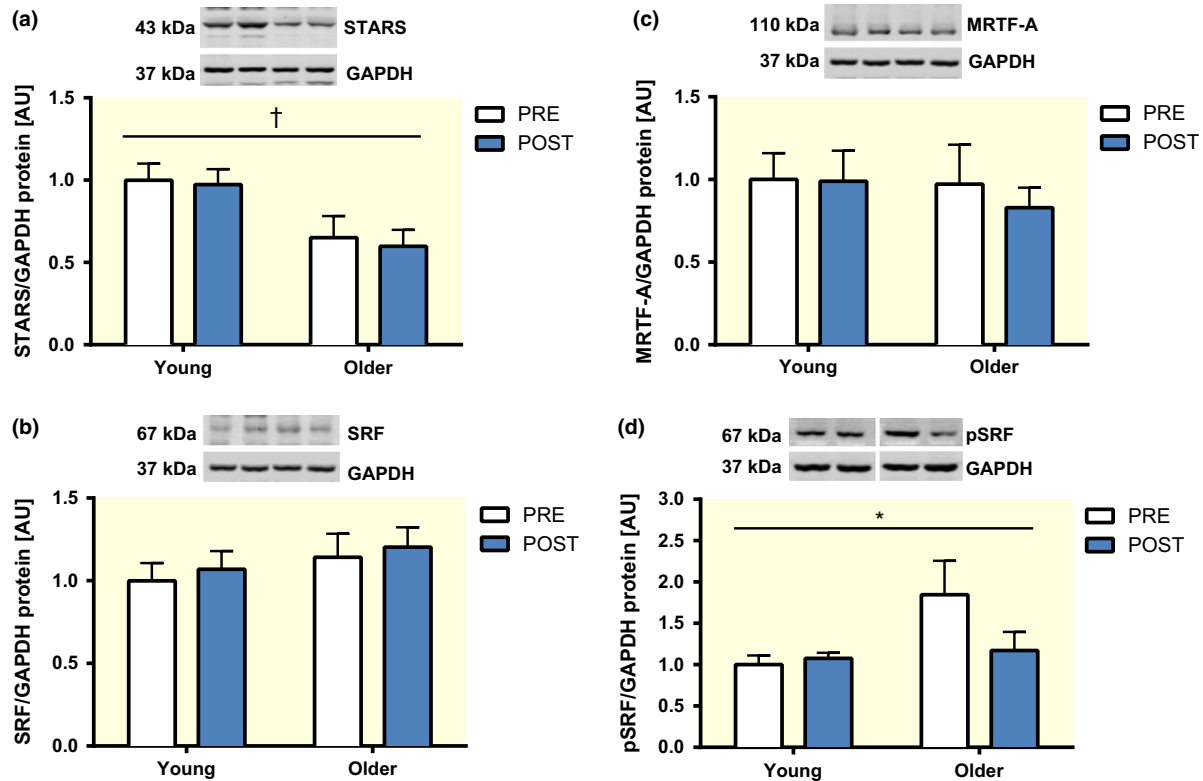


**Figure 1** Striated muscle activator of Rho signalling (*STARS*), serum response factor (*SRF*) and myocardin-related transcription factor-A (*MRTF-A*) mRNA expression levels in skeletal muscle from young and older subjects pre- and post-exercise. \*Main effect of exercise,  $P < 0.05$ . †Main effect of exercise,  $P < 0.001$ .

significant decrease in *STARS* protein expression was observed in older subjects when compared to young subjects (main effect of age,  $P < 0.01$ ) (Fig. 2a). Phospho-SRF protein levels were greater in older subjects than in young subjects (main effect of age,  $P < 0.05$ ) (Fig. 2d). Age had no effect on *MRTF-A* or total SRF protein expression (Fig. 2b,c).

#### Age and exercise regulation of miRNAs targeting members of the STARS pathway

The miRNA array analysis returned a total of 26 miRNAs that were significant for one or more of the contrasts studied, indicating that the expression levels of these miRNAs varied with age, exercise or a combination of both factors (previously reported in Zacharewicz *et al.* 2014). Of the miRNAs known to directly



**Figure 2** Striated muscle activator of Rho signalling (STARS), serum response factor (SRF) and myocardin-related transcription factor-A (MRTF-A) and phospho-SRF protein expression levels in skeletal muscle from young and older subjects pre- and post-exercise. Exercise had no effect on any of the proteins measured. \*Main effect of age,  $P < 0.05$ . †Main effect of age,  $P < 0.01$ . Note that the reported statistical significance of any comparisons is based on analyses of the transformed data, but the reported means  $\pm$  SEMs represent the original (untransformed) scale. Note that non-contiguous gel lanes are demarcated by white spaces; no adjustment to digital images does not alter the information contained therein.

target SRF or MRTF-A, miR-320a and miR-483-5p were regulated with age in our model (Fig. 3). No change was observed for miR-9, miR-133a, miR-150 and miR-206 (Fig. S2), and miR-31 and miR-200 levels were expressed below the threshold for detection. Both miR-320a and miR-483-5p expression levels were higher in older than in young subjects (main effect of age,  $P < 0.01$  and  $P < 0.001$  respectively) (Fig. 3a,c). A significant negative correlation ( $P = 0.04$ ;  $r = 0.37$ ) was observed between *Srf* mRNA and miR-483-5p, but not miR-320a, levels when all subjects (pre- and post-exercise) were analysed (Fig. 3b,d).

#### Identification of new miRNAs potentially targeting STARS

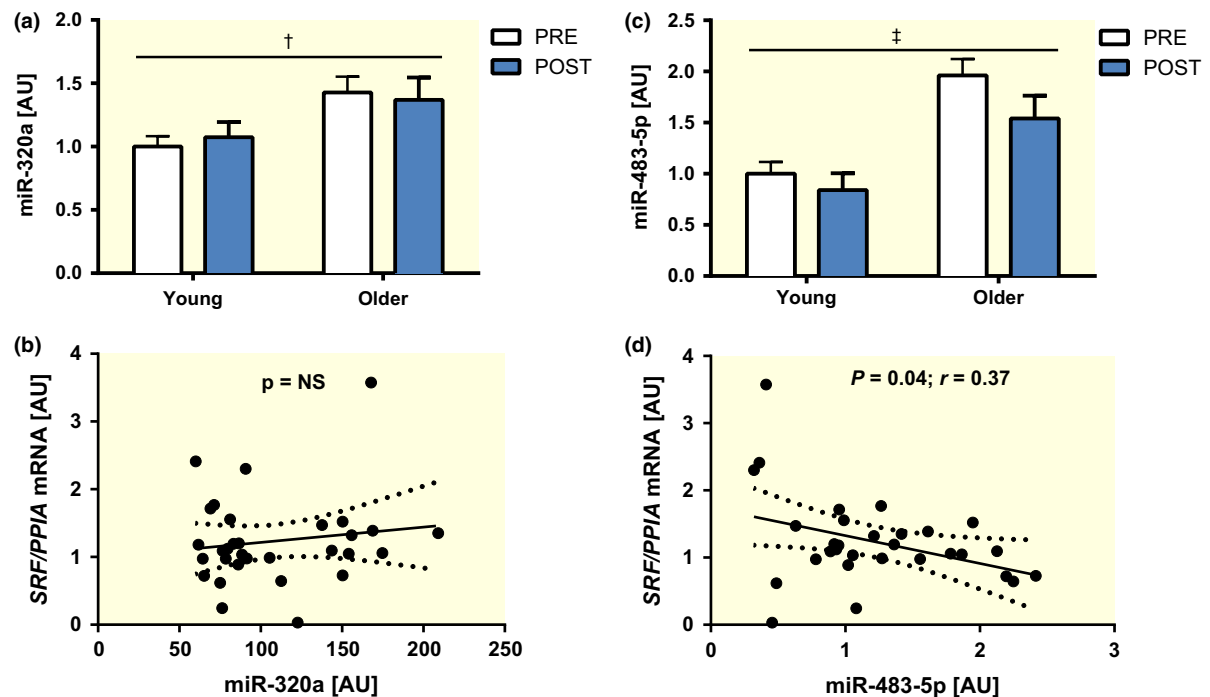
As there has been no validation of a miRNA that regulates STARS, we performed a miRNA prediction analysis using miRwalk on the subset of 26 miRNAs that were significantly regulated in our model (Zacharewicz *et al.* 2014). Of these, miR-520g-3p,

miR-539-5p and miR-628-5p were predicted to target the human *STARS* transcript by four prediction software programs included in the miRwalk software. Figure 4 displays the expression levels of miR-520g-3p, miR-539-5p and miR-628-5p in young and older subjects 2 h after exercise. MiR-520g-3p was significantly reduced post-exercise in young subjects only ( $P < 0.05$ ) (Fig. 4a). There was a main effect of age for miR-539-5p, which expression was greater in older subjects ( $P < 0.05$ ) (Fig. 4b). Finally, there was a significant interaction effect for miR-628-5p expression levels ( $P < 0.05$ ), which were reduced post-exercise in young subjects and lower at rest in the older subjects ( $P < 0.05$  and  $P < 0.01$  respectively) (Fig. 4c).

#### Luciferase reporter assay

To confirm whether miR-628-5p, miR-520g-3p or miR-539-5p was able to directly bind and regulate the *STARS* 3'UTR, HEK293 cells were cotransfected with a reporter plasmid containing the full-length *STARS*





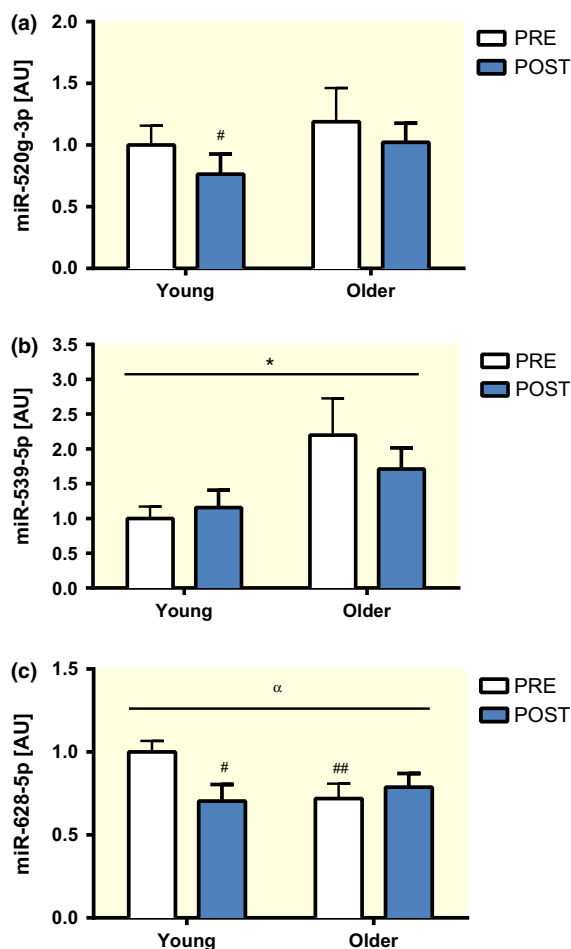
**Figure 3** MiR-320a and miR-483-5p expression and linear correlations with SRF mRNA levels in skeletal muscle from young and older subjects pre- and post-exercise. †Main effect of age,  $P < 0.01$ . ‡Main effect of age,  $P < 0.001$ . NS, not statistically significant.

3'UTR as well as either a miR-628-5p, miR-520g-3p or miR-539-5p mimic, an irrelevant miRNA that did not have a predicted binding site on the *STARS* 3'UTR or no mimic at all. Twenty-four hours after the cotransfection of the reporter plasmid and mimics, there was 30% reduction in Nanoluc luciferase activity ( $P < 0.05$ ) (Fig. 5a) in the cells containing the miR-628-5p mimic when compared to cells transfected with an irrelevant miRNA. When completing the reporter assay using the miR-520g-3p or miR-539-5p mimics, there was no reduction in the luminescence levels demonstrating that these miRNAs did not bind to the *STARS* 3'UTR (data not shown). We then sought to investigate the miR-628-5p putative binding site on the *STARS* 3'UTR. HEK293 cells were again cotransfected with the miR-628-5p mimic or an irrelevant miRNA; however, this time we used a reporter plasmid that contained a shorter version of the *STARS* 3'UTR. This shorter version contained only the putative miR-628-5p binding site as well as 10 base pairs either side of the site. As an additional control, cells were also transfected with this shorter *STARS* 3'UTR reporter plasmid; however, the miR-628-5p binding site was mutated. Twenty-four hours after the cotransfection of reporter plasmid and the mimics, there was a 32% reduction in Nanoluc luciferase activity ( $P < 0.001$ ) (Fig. 5b) in the cells containing the miR-628-5p mimic when compared to cells transfected

with an irrelevant miRNA. No differences were observed when the cells were transfected with the *STARS* 3'UTR reporter containing the mutated miR-628-5p binding site.

## Discussion

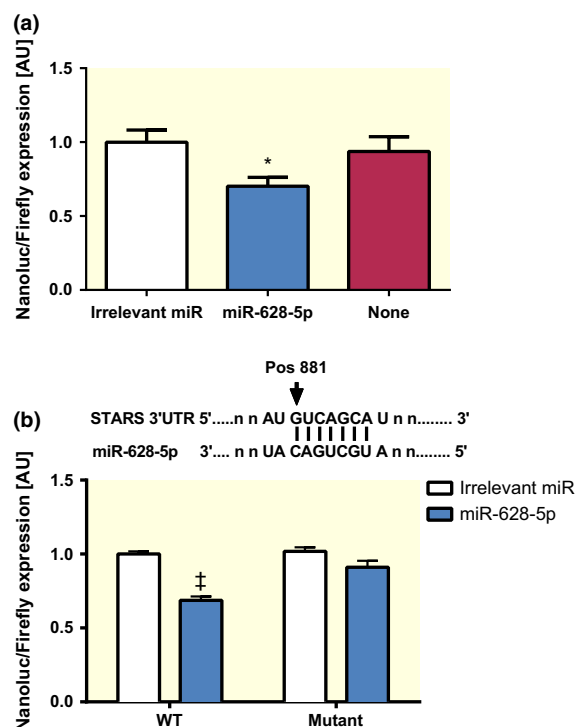
The *STARS* signalling pathway plays an essential role in skeletal muscle adaptation to mechanical stimuli (Lamon *et al.* 2014). Previous studies have reported a reduction in the mRNA and protein levels of members of the *STARS*/SRF signalling axis with ageing, but the effects of age on the regulation of the *STARS* pathway in human skeletal muscle have not been investigated. We report for the first time that *STARS* protein, but not mRNA, levels are significantly decreased in human skeletal muscle from older when compared to the young subjects. A reduction in *Stars* gene expression was previously reported in skeletal muscle from aged mice (Sakuma *et al.* 2008) and pigs (Peng *et al.* 2008). This discrepancy between gene and protein expression suggests the existence of alternative post-transcriptional regulatory processes that may include regulation via miRNAs. Although its function in skeletal muscle has not been fully elucidated, *STARS* is anticipated to be necessary for muscle cell development and repair. Overexpressing the *STARS* protein in porcine smooth muscle cells and in the A10 rat



**Figure 4** miR-520g-3p, miR-539-5p and miR-628-5p expression levels in skeletal muscle from young and older subjects pre- and post-exercise. \*Main effect of age,  $P < 0.05$ .  $^{\alpha}$  Main interaction effect,  $P < 0.05$ . #significantly different from PRE,  $P < 0.05$ . ##significantly different from Young,  $P < 0.01$ .

vascular smooth muscle cell line (Ounzain *et al.* 2008) enhanced proliferation and overexpressing STARS accelerated C<sub>2</sub>C<sub>12</sub> cell differentiation (Wallace *et al.* 2016). The elderly display a reduction in satellite cell (myoblast) number and activation (Corbu *et al.* 2010, Walker *et al.* 2012) leading to impaired regenerative capacity. Reduced activity of STARS might therefore contribute to the age-related muscle atrophy process by impeding muscle cell regeneration in the elderly.

We did not observe an age-related decrease in SRF mRNA or in the total and phosphorylated forms of the SRF protein. *Srf* mRNA levels were also similar in the gastrocnemius muscle of young (3 months) when compared to old (15 month) mice (Lahoute *et al.* 2008). However, in whole muscle homogenates, total SRF protein levels were reduced in old (Lahoute *et al.* 2008) and sarcopaenic (24 month) mice (Sakuma



**Figure 5** Luciferase reporter assay. (a) Nanoluc luciferase activity was assessed in HEK293 cells following cotransfection with 150 ng pNanoglo2 vector containing the full-length STARS 3'UTR and either 5 nM miR-628-5p mimic, 5 nM of an irrelevant miRNA (negative control) or no miR. Experiment was conducted once using  $n = 6$  wells per group. \*Significantly different from irrelevant miR ( $P < 0.05$ ). (b) Nanoluc luciferase activity was assessed in HEK293 cells following cotransfection with 150 ng pNanoglo2 vector containing either the putative miR-628-5p binding site of STARS 3'UTR (CGUUUCAUUACaugucagcaUAUACGAGUCACCGCGGG) or its mutant control (CGUUUCAUUACuucguuuuaUAUACGAGUCACCGCGGG) and either 5 nM miR-628-5p mimic or 5 nM of an irrelevant miRNA (negative control). The putative binding site between miR-628-5p and the STARS 3'UTR is schematically represented above the graph. ‡Significantly different from irrelevant miR ( $P < 0.001$ ). Experiments were repeated three times using  $n = 6$  wells per group.

*et al.* 2008) when compared with young mice. In contrast, analysis of the nuclear extracts following muscle protein fractionation revealed that the protein levels of the SRF transcriptional coactivator MRTF-A were lower in sarcopaenic mice when compared with young mice, with no difference in SRF (Sakuma *et al.* 2008). Nuclear SRF represents the active, phosphorylated form of SRF. Combined with our observed increase in nuclear pSRF in human muscle from older subjects, these results suggest that ageing skeletal muscle maintains its ability to regulate gene transcription via SRF. The reason and mechanism for elevated basal levels of

phosphorylated SRF in muscle from older subjects is not known. SRF is phosphorylated and activated by numerous kinases, including, but not limited to, casein kinase, CaM kinase IV and MAPKAP kinase 2 (Manak *et al.* 1990, Misra *et al.* 1991, Janknecht *et al.* 1992, Marais *et al.* 1992, Heidenreich *et al.* 1999). In addition to MRTF-A, several factors co-activate SRF transcription, such as inositol polyphosphate multikinase (IPMK) (Kim *et al.* 2013), Elk-1 (Janknecht & Nordheim 1992), cardiogenic homeodomain factor Nkx-2.5 (Chen & Schwartz 1996), SRF accessory protein (SAP-1) (Dalton & Treisman 1992), p65/NF-kappaB (Franzoso *et al.* 1996) and GATA binding protein 4 (GATA-4) (Belaguli *et al.* 2000). In the absence of MRTF-A, these other coactivators may play a compensatory role in assisting with SRF gene transcription. Due to limited sample availability, we have not determined whether these kinases or alternative coactivators were upregulated in our model. Elevated phosphorylated SRF levels in the older subjects may reflect an attempt to maintain muscle size, cell survival and muscle repair (Miano 2010). In relation to the exercise intervention, a high basal SRF phosphorylation level in older subjects might be reflective of an already maximal activation of the SRF protein at rest, and therefore reduce the capacity for further activation following an anabolic stress, such as resistance exercise.

The regulation of members of the STARS pathway in skeletal muscle is sensitive to the mechanical stress induced by resistance exercise in untrained younger subjects (MacNeil *et al.* 2010, Lamon *et al.* 2013, Vissing *et al.* 2013), but its regulation in older subjects has not been investigated. Here, we observed an increase in the mRNA levels of members of the STARS signalling pathway 2 h after an acute bout of resistance exercise that was independent of age. Our results revealed no changes in the protein levels of the members of the STARS signalling pathway in response to exercise. Any potential increase may possibly occur later in the post-exercise recovery period. Indeed, two recent studies from our group investigated the regulation of the STARS signalling pathway following acute exercise in trained and untrained young subjects (Lamon *et al.* 2013, Vissing *et al.* 2013). In line with the results of the present study, we only reported minor changes in protein expression within the 3 h following acute exercise (Vissing *et al.* 2013). The early induction of STARS in response to resistance exercise is believed to trigger intracellular signals responsible for muscle adaptation to exercise; however this has not yet been experimentally validated. While the precise mechanisms involved are unknown, it has been suggested (Arai *et al.* 2002, Lamon *et al.* 2013, 2014) that this adaptive response may protect against

contraction-induced muscle damage, in addition to helping regeneration and repair, two processes that are commonly disrupted in elderly subjects (Brack & Rando 2007). Reduced basal levels of the STARS protein in older subjects may therefore reflect a reduced capacity of STARS to protect the muscle following exercise.

A limitation when recruiting community-dwelling older subjects to participate in an exercise trial is that they tend to be physically active and therefore not necessarily representative of the average elderly population. We have previously reported that the older subject cohort used in this study was not considered sarcopaenic (Zacharewicz *et al.* 2014). However, at present, this study is the only one that has measured and compared the regulation of the STARS signalling pathway, at rest and following resistance exercise, using an appropriately powered cohort of young and older subjects. Discrepancies in observations made in young and sarcopaenic mice (Sakuma *et al.* 2008) vs. young and older men in the present study may be imputable to species differences or to the fact that our subjects were not sufficiently sarcopaenic. Therefore, our findings might not be representative of a more sedentary and/or sarcopaenic human population.

miRNAs are important regulators of skeletal muscle health (Zacharewicz *et al.* 2013) that regulate gene transcription by directly degrading mRNAs (Huili *et al.* 2010), inhibiting protein translation (Lee *et al.* 2004a, Wightman *et al.* 2004, Humphreys *et al.* 2005, Pillai *et al.* 2005) and in some cases stabilizing mRNAs (Vasudevan & Steitz 2007, Vasudevan *et al.* 2007, Ørom *et al.* 2008). The conditions and level of specificity with which miRNAs interact with their respective targets remain mostly unclear. Within the scope of this study, we investigated the regulation of the miRNAs known to target members of the STARS signalling pathway. The expression levels of miR-320a and miR-483-5p, two miRNAs negatively regulating SRF transcription (Qiao *et al.* 2011, Chen *et al.* 2015), increased with age. MiR-483-5p is embedded in the intron of the insulin-like growth factor 2 (IGF2) gene and inhibits SRF mRNA and protein expression by directly targeting the SRF transcript in endothelial cells (Qiao *et al.* 2011). While SRF increased with exercise in both subject groups, we observed a concomitant decrease in miR-483-5p levels, which resulted in significant negative linear correlation. As miR-483-5p directly binds to the SRF 3'UTR resulting in its suppression (Qiao *et al.* 2011), the resistance exercise-induced downregulation of miR-483-5p may release its inhibition on SRF, therefore contributing to the upregulation of the latter. Whether increased STARS expression and attenuated miR-483-5p expression has an additive effect on SRF transcription would



be of interest to determine. Similarly, miR-320a can also target the SRF transcript resulting in inhibition of cell proliferation and promoting apoptosis in human-derived endothelium cells (Chen *et al.* 2015). When compared to healthy age-matched controls, miR-320a is upregulated in several conditions associated with skeletal muscle degeneration and atrophy, including limb girdle muscular dystrophy type 2A, Miyoshi myopathy, Nemaline myopathy, inclusion body myositis and polymyocytosis (Eisenberg *et al.* 2007). MiR-320a is also known to play a role in energy metabolism. It directly inhibits the rate-limiting step of glycolysis by targeting the enzyme phosphofructokinase and its expression was reduced in C<sub>2</sub>C<sub>12</sub> myotubes and other biological systems when subjected to oxidative stress (Tang *et al.* 2012). We have previously suggested that STARS regulates energy metabolism in the muscle fibre and have shown that STARS shifts the muscle cell to a more oxidative phenotype (Wallace & Russell 2013). Whether this process involves miR-320a is unknown.

Of the three miRNAs predicted to target STARS, miR-628-5p interacted with its putative binding sequence on the STARS 3'UTR and repressed STARS transcription *in vitro*. While mainly studied in cancer models, it was suggested that miR-628-5p promotes the expression of FOXO3a, a regulator of skeletal muscle atrophy, in leukaemic progenitor cells in response to IL-3 treatment (Favreau & Sathyanarayana 2012), although no regulation of FOXO3a gene or protein was observed in this cohort (Stefanetti *et al.* 2015). The role and regulation of miR-628-5p in skeletal muscle is relatively unknown. One study has reported that miR-628-5p expression in foetal skeletal muscle in human facioscapulohumeral muscular dystrophy (FSHD) is upregulated at 14 weeks of foetal development but down regulated at 22 weeks, when compared with age-matched controls (Portilho *et al.* 2015). Whether miR-628-5p has an acute effect on the regulation of STARS mRNA post-exercise remains to be determined. Clearly more studies are required to establish the precise role of miR-628-5p in skeletal muscle growth, repair and function over the lifespan.

In conclusion, we demonstrated that although the resting levels of the STARS protein are lower in skeletal muscle of older when compared to young subjects, this did not affect the resistance exercise-induced upregulation of STARS and SRF mRNA seen in both age groups. These findings did not translate to the SRF protein, which in addition displayed higher phosphorylation levels in older than in young subjects. Finally, we identified for the first time that miR-628-5p is a resistance exercise responsive miRNA that directly binds the STARS 3'UTR to reduce its transcription *in vitro*.

## Conflict of interest

The authors have no conflict of interest to declare.

This work was supported by the Swiss National Science Foundation (PBLAP3-131833 and PBLAP3-137051 to SL); an Alfred Deakin Postdoctoral Fellowship from Deakin University (RM24071 to SL); the Deakin University Central Research Grants Scheme (RM24183 to SL and APR); and a National Health and Medical Research Council project grant (APP1046501 to APR).

## References

- Arai, A., Spencer, J.A. & Olson, E.N. 2002. STARS, a striated muscle activator of Rho signaling and serum response factor-dependent transcription. *J Biol Chem* **277**, 24453–24459.
- Arthur, S.T. & Cooley, I.D. 2012. The effect of physiological stimuli on sarcopenia; impact of Notch and Wnt signaling on impaired aged skeletal muscle repair. *Int J Biol Sci* **8**, 731–760.
- Belaguli, N.S., Sepulveda, J.L., Nigam, V., Charron, F., Nemer, M. & Schwartz, R.J. 2000. Cardiac tissue enriched factors serum response factor and GATA-4 are mutual coregulators. *Mol Cell Biol* **20**, 7550–7558.
- Boirie, Y. 2009. Physiopathological mechanism of sarcopenia. *J Nutr Health Aging* **13**, 717–723.
- Brack, A.S. & Rando, T.A. 2007. Intrinsic changes and extrinsic influences of myogenic stem cell function during aging. *Stem Cell Rev* **3**, 226–237.
- Braun, T. & Gautel, M. 2011. Transcriptional mechanisms regulating skeletal muscle differentiation, growth and homeostasis. *Nat Rev Mol Cell Biol* **12**, 349–361.
- Brennecke, J., Stark, A., Russell, R.B. & Cohen, S.M. 2005. Principles of microRNA–target recognition. *PLoS Biol* **3**, e85.
- Buller, B., Chopp, M., Ueno, Y., Zhang, L., Zhang, R.L., Morris, D., Zhang, Y. & Zhang, Z.G. 2012. Regulation of serum response factor by miRNA-200 and miRNA-9 modulates oligodendrocyte progenitor cell differentiation. *Glia* **60**, 1906–1914.
- Chen, C.Y. & Schwartz, R.J. 1996. Recruitment of the tinman homolog Nkx-2.5 by serum response factor activates cardiac alpha-actin gene transcription. *Mol Cell Biol* **16**, 6372–6384.
- Chen, C., Wang, Y., Yang, S., Li, H., Zhao, G., Wang, F., Yang, L. & Wang, D.W. 2015. MiR-320a contributes to atherogenesis by augmenting multiple risk factors and down-regulating SRF. *J Cell Mol Med* **19**, 970–985.
- Corbu, A., Scaramozza, A., Badiali-DeGiorgi, L., Tarantino, L., Papa, V., Rinaldi, R., D'Alessandro, R., Zavatta, M., Laus, M., Lattanzi, G. & Cenacchi, G. 2010. Satellite cell characterization from aging human muscle. *Neurol Res* **32**, 63–72.
- Dalton, S. & Treisman, R. 1992. Characterization of SAP-1, a protein recruited by serum response factor to the c-fos serum response element. *Cell* **68**, 597–612.
- Dedkov, E.I., Kostrominova, T.Y., Borisov, A.B. & Carlson, B.M. 2003. MyoD and myogenin protein expression in

- skeletal muscles of senile rats. *Cell Tissue Res* **311**, 401–416.
- Dorrens, J. & Rennie, M.J. 2003. Effects of ageing and human whole body and muscle protein turnover. *Scand J Med Sci Sports* **13**, 26–33.
- Eisenberg, I., Eran, A., Nishino, I., Moggio, M., Lamperti, C., Amato, A.A., Lidov, H.G., Kang, P.B., North, K.N., Mitrani-Rosenbaum, S. et al. 2007. Distinctive patterns of microRNA expression in primary muscular disorders. *Proc Natl Acad Sci USA* **104**, 17016–17021.
- Favreau, A.J. & Sathyanarayana, P. 2012. miR-590-5p, miR-219-5p, miR-15b and miR-628-5p are commonly regulated by IL-3, GM-CSF and G-CSF in acute myeloid leukemia. *Leuk Res* **36**, 334–341.
- Franzoso, G., Carlson, L., Brown, K., Daucher, M.B., Bressler, P. & Siebenlist, U. 1996. Activation of the serum response factor by p65/NF-kappaB. *EMBO J* **15**, 3403–3412.
- Gineitis, D. & Treisman, R. 2001. Differential usage of signal transduction pathways defines two types of serum response factor target gene. *J Biol Chem* **276**, 24531–24539.
- Heidenreich, O., Neininger, A., Schratt, G., Zinck, R., Cahill, M.A., Engel, K., Kotlyarov, A., Kraft, R., Kostka, S., Gaestel, M. & Nordheim, A. 1999. MAPKAP kinase 2 phosphorylates serum response factor *in vitro* and *in vivo*. *J Biol Chem* **274**, 14434–14443.
- Hu, Z. & Bruno, A.E. 2011. The influence of 3'UTRs on microRNA function inferred from human SNP data. *Comp Funct Genomics*, **2011**, 910769.
- Huili, G., Ingolia, N.T., Weissman, J.S. & Bartel, D.P. 2010. Mammalian microRNAs predominantly act to decrease target mRNA levels. *Nature* **466**, 835–840.
- Humphreys, D.T., Westman, B.J., Martin, D.I.K. & Preiss, T. 2005. MicroRNAs control translation initiation by inhibiting eukaryotic initiation factor 4E/cap and poly(A) tail function. (English). *Proc Natl Acad Sci USA* **102**, 16961–16966.
- Janknecht, R. & Nordheim, A. 1992. Elk-1 protein domains required for direct and SRF-assisted DNA-binding. *Nucleic Acids Res* **20**, 3317–3324.
- Janknecht, R., Hipkind, R.A., Houthaeve, T., Nordheim, A. & Stunnenberg, H.G. 1992. Identification of multiple SRF N-terminal phosphorylation sites affecting DNA binding properties. *EMBO J* **11**, 1045–1054.
- Jin, C., Zang, C., Wei, G., Cui, K., Peng, W., Zhao, K. & Felsenfeld, G. 2009. H3.3/H2A.Z double variant-containing nucleosomes mark 'nucleosome-free regions' of active promoters and other regulatory regions. *Nat Genet* **41**, 941–945.
- Katsura, A., Suzuki, H.I., Ueno, T., Mihira, H., Yamazaki, T., Yasuda, T., Watabe, T., Mano, H., Yamada, Y. & Miyazono, K. 2016. MicroRNA-31 is a positive modulator of endothelial-mesenchymal transition and associated secretory phenotype induced by TGF-beta. *Genes Cells* **21**, 99–116.
- Kim, E., Tyagi, R., Lee, J.Y., Park, J., Kim, Y.R., Beon, J., Chen, P.Y., Cha, J.Y., Snyder, S.H. & Kim, S. 2013. Inositol polyphosphate multikinase is a coactivator for serum response factor-dependent induction of immediate early genes. *Proc Natl Acad Sci USA* **110**, 19938–19943.
- Kumar, V., Selby, A., Rankin, D., Patel, R., Atherton, P., Hildebrandt, W., Williams, J., Smith, K., Seynnes, O., Hiscock, N. & Rennie, M.J. 2009. Age-related differences in the dose-response relationship of muscle protein synthesis to resistance exercise in young and old men. *J Physiol* **587**, 211–217.
- Kuwahara, K., Barrientos, T., Pipes, G.C.T., Li, S. & Olson, E.N. 2005. Muscle-specific signaling mechanism that links actin dynamics to serum response factor. *Mol Cell Biol* **25**, 3173–3181.
- Lahoute, C., Sotiropoulos, A., Favier, M., Guillet-Deniau, I., Charvet, C., Ferry, A., Butler-Browne, G., Metzger, D., Tuil, D. & Daegelen, D. 2008. Premature aging in skeletal muscle lacking serum response factor. *PLoS ONE* **3**, e3910.
- Lamon, S., Wallace, M.A., Leger, B. & Russell, A.P. 2009. Regulation of STARS and its downstream targets suggest a novel pathway involved in human skeletal muscle hypertrophy and atrophy. *J Physiol* **587**, 1795–1803.
- Lamon, S., Wallace, M.A., Stefanetti, R.J., Rahbek, S.K., Vendelbo, M.H., Russell, A.P. & Vissing, K. 2013. Regulation of the STARS signaling pathway in response to endurance and resistance exercise and training. *Pflugers Arch* **465**, 1317–1325.
- Lamon, S., Wallace, M.A. & Russell, A.P. 2014. The STARS signaling pathway: a key regulator of skeletal muscle function. *Pflugers Arch* **466**, 1659–1671.
- Lee, S.W., Dai, G., Hu, Z., Wang, X., Du, J. & Mitch, W.E. 2004a. Regulation of muscle protein degradation: coordinated control of apoptotic and ubiquitin-proteasome systems by phosphatidylinositol 3 kinase. *J Am Soc Nephrol* **15**, 1537–1545.
- Lee, Y., Kim, M., Han, J., Yeom, K.-H., Lee, S., Baek, S.H. & Kim, V.N. 2004b. MicroRNA genes are transcribed by RNA polymerase II. *EMBO J* **23**, 4051–4060.
- Léger, B., Derave, W., De Bock, K., Hespel, P. & Russell, A.P. 2008. Human sarcopenia reveals an increase in SOCS-3 and myostatin and a reduced efficiency of Akt phosphorylation. *Rejuvenation Res* **11**, 163–175B.
- Liu, N., Bezprozvannaya, S., Williams, A.H., Qi, X., Richardson, J.A., Bassel-Duby, R. & Olson, E.N. 2008. microRNA-133a regulates cardiomyocyte proliferation and suppresses smooth muscle gene expression in the heart. *Genes Dev* **22**, 3242–3254.
- Liu, W., Liu, Y., Zhang, Y., Zhu, X., Zhang, R., Guan, L., Tang, Q., Jiang, H., Huang, C. & Huang, H. 2015. MicroRNA-150 protects against pressure overload-induced cardiac hypertrophy. *J Cell Biochem* **116**, 2166–2176.
- MacNeil, L.G., Melov, S., Hubbard, A.E., Baker, S.K. & Tarnopolsky, M.A. 2010. Eccentric exercise activates novel transcriptional regulation of hypertrophic signaling pathways not affected by hormone changes. *PLoS ONE* **5**, e10695.
- Mahadeva, H., Brooks, G., Lodwick, D., Chong, N.W. & Samani, N.J. 2002. ms1, a novel stress-responsive, muscle-specific gene that is up-regulated in the early stages of pressure overload-induced left ventricular hypertrophy. *FEBS Lett* **521**, 100–104.
- Manak, J.R., de Bisschop, N., Kris, R.M. & Prywes, R. 1990. Casein kinase II enhances the DNA binding activity of serum response factor. *Genes Dev* **4**, 955–967.

- Marais, R.M., Hsuan, J.J., McGuigan, C., Wynne, J. & Treisman, R. 1992. Casein kinase II phosphorylation increases the rate of serum response factor-binding site exchange. *EMBO J* **11**, 97–105.
- Marsh, D.R., Criswell, D.S., Carson, J.A. & Booth, F.W. 1997. Myogenic regulatory factors during regeneration of skeletal muscle in young, adult, and old rats. *J Appl Physiol* **83**, 1270–1275.
- Miano, J.M. 2010. Role of serum response factor in the pathogenesis of disease. *Lab Invest* **90**, 1274–1284.
- Misra, R.P., Rivera, V.M., Wang, J.M., Fan, P.D. & Greenberg, M.E. 1991. The serum response factor is extensively modified by phosphorylation following its synthesis in serum-stimulated fibroblasts. *Mol Cell Biol* **11**, 4545–4554.
- Olsen, P.H. & Ambros, V. 1999. The lin-4 regulatory RNA controls developmental timing in *Caenorhabditis elegans* by blocking LIN-14 protein synthesis after the initiation of translation. *Dev Biol* **216**, 671–680.
- Olson, E.N. & Nordheim, A. 2010. Linking actin dynamics and gene transcription to drive cellular motile functions. *Nat Rev Mol Cell Biol* **11**, 353–365.
- Ørom, U.A., Nielsen, F.C. & Lund, A.H. 2008. MicroRNA-10a binds the 5'UTR of ribosomal protein mRNAs and enhances their translation. *Mol Cell* **30**, 460–471.
- Ounzain, S., Dacwag, C.S., Samani, N.J., Imbalzano, A.N. & Chong, N.W. 2008. Comparative in silico analysis identifies bona fide MyoD binding sites within the Myocyte stress 1 gene promoter. *BMC Mol Biol* **9**, 50.
- Peng, Y.B., Guan, H.P., Fan, B., Zhao, S.H., Xu, X.W., Li, K., Zhu, M.J., Yerle, M. & Liu, B. 2008. Molecular characterization and expression pattern of the porcine STARS, a striated muscle-specific expressed gene. *Biochem Genet* **46**, 644–651.
- Phillips, S.M. 2012. Nutrient-rich meat proteins in offsetting age-related muscle loss. *Meat Sci* **92**, 174–178.
- Pillai, R.S., Bhattacharyya, S.N., Artus, C.G., Zoller, T., Cougot, N., Basyuk, E., Bertrand, E. & Filipowicz, W. 2005. Inhibition of translational initiation by Let-7 microRNA in human cells. *Science* **309**, 1573–1576.
- Portilho, D.M., Alves, M.R., Kratassiouk, G., Roche, S., Magdinier, F., de Santana, E.C., Polesskaya, A., Harel-Bellan, A., Mouly, V., Savino, W., Butler-Browne, G. & Dumonceaux, J. 2015. miRNA expression in control and FSHD fetal human muscle biopsies. *PLoS ONE* **10**, e0116853.
- Qiao, Y., Ma, N., Wang, X., Hui, Y., Li, F., Xiang, Y., Zhou, J., Zou, C., Jin, J., Lv, G., Jin, H. & Gao, X. 2011. MiR-483-5p controls angiogenesis *in vitro* and targets serum response factor. *FEBS Lett* **585**, 3095–3100.
- Sakuma, K., Akiho, M., Nakashima, H., Akima, H. & Yasuhara, M. 2008. Age-related reductions in expression of serum response factor and myocardin-related transcription factor A in mouse skeletal muscles. *Biochim Biophys Acta* **1782**, 453–461.
- Shadrach, J.L. & Wagers, A.J. 2011. Stem cells for skeletal muscle repair. *Philos Trans R Soc Lond B Biol Sci* **366**, 2297–2306.
- Smith-Vikos, T. & Slack, F.J. 2012. MicroRNAs and their roles in aging. *J Cell Sci* **125**, 7–17.
- Stefanetti, R.J., Zacharewicz, E., Della Gatta, P., Garnham, A., Russell, A.P. & Lamon, S. 2014. Ageing has no effect on the regulation of the ubiquitin proteasome-related genes and proteins following resistance exercise. *Front Physiol* **5**, 30.
- Stefanetti, R.J., Lamon, S., Wallace, M., Vendelbo, M.H., Russell, A.P. & Vissing, K. 2015. Regulation of ubiquitin proteasome pathway molecular markers in response to endurance and resistance exercise and training. *Pflugers Arch* **467**, 1523–1537.
- Tang, H., Lee, M., Sharpe, O., Salamone, L., Noonan, E.J., Hoang, C.D., Levine, S., Robinson, W.H. & Shrager, J.B. 2012. Oxidative stress-responsive microRNA-320 regulates glycolysis in diverse biological systems. *FASEB J* **26**, 4710–4721.
- Troidl, K., Ruding, I., Cai, W.J., Mucke, Y., Grosseckler, L., Piotrowska, I., Apfelbeck, H., Schierling, W., Volger, O.L., Horrevoets, A.J., Grote, K., Schmitz-Rixen, T., Schaper, W. & Troidl, C. 2009. Actin-binding rho activating protein (Abra) is essential for fluid shear stress-induced arteriogenesis. *Arterioscler Thromb Vasc Biol* **29**, 2093–2101.
- Vasudevan, S. & Steitz, J.A. 2007. AU-rich-element-mediated upregulation of translation by FXR1 and argonaute 2. *Cell* **128**, 1105–1118.
- Vasudevan, S., Tong, Y. & Steitz, J.A. 2007. Switching from repression to activation: microRNAs can up-regulate translation. *Science* **318**, 1931–1934.
- Vissing, K., Rahbek, S.K., Lamon, S., Farup, J., Stefanetti, R.J., Wallace, M.A., Vendelbo, M.H. & Russell, A. 2013. Effect of resistance exercise contraction mode and protein supplementation on members of the STARS signalling pathway. *J Physiol* **591**, 3749–3763.
- Walker, D.K., Fry, C.S., Drummond, M.J., Dickinson, J.M., Timmerman, K.L., Gundermann, D.M., Jennings, K., Volpi, E. & Rasmussen, B.B. 2012. PAX7+ satellite cells in young and older adults following resistance exercise. *Muscle Nerve* **46**, 51–59.
- Wallace, M.A. & Russell, A.P. 2013. Striated muscle activator of Rho signaling is required for myotube survival but does not influence basal protein synthesis or degradation. *Am J Physiol Cell Physiol* **305**, C414–C426.
- Wallace, M.A., Hock, M.B., Hazen, B.C., Kralli, A., Snow, R.J. & Russell, A.P. 2011. Striated muscle activator of Rho signalling (STARS) is a PGC-1alpha/oestrogen-related receptor-alpha target gene and is upregulated in human skeletal muscle after endurance exercise. *J Physiol* **589**, 2027–2039.
- Wallace, M.A., Lamon, S. & Russell, A.P. 2012. The regulation and function of the striated muscle activator of rho signaling (STARS) protein. *Front Physiol* **3**, 469.
- Wallace, M.A., Della Gatta, P.A., Ahmad Mir, B., Kowalski, G.M., Kloehn, J., McConville, M.J., Russell, A.P. & Lamon, S. 2016. Overexpression of striated muscle activator of rho signaling (STARS) increases C2C12 skeletal muscle cell differentiation. *Front Physiol* **7**, 7.
- Wightman, B., Ha, I. & Ruvkun, G. 2004. Posttranscriptional regulation of the heterochronic gene lin-14 by lin-4 mediates temporal pattern formation in *C. elegans*. *Cell* **116**, 855–862.

- Zacharewicz, E., Lamon, S. & Russell, A.P. 2013. MicroRNAs in skeletal muscle and their regulation with exercise, ageing, and disease. *Front Physiol* 4, 266.
- Zacharewicz, E., Della Gatta, P., Reynolds, J., Garnham, A., Crowley, T., Russell, A.P. & Lamon, S. 2014. Identification of microRNAs linked to regulators of muscle protein synthesis and regeneration in young and old skeletal muscle. *PLoS ONE* 9, e114009.
- Zaleska, M., Fogl, C., Kho, A.L., Ababou, A., Ehler, E. & Pfuhl, M. 2015. The cardiac stress response factor Ms1 can bind to DNA and has a function in the nucleus. *PLoS ONE* 10, e0144614.
- Zhang, W.L., Lv, W., Sun, S.Z., Wu, X.Z. & Zhang, J.H. 2015. miR-206 inhibits metastasis-relevant traits by degrading MRTF-A in anaplastic thyroid cancer. *Int J Oncol* 47, 133–142.

### Physiological relevance

Striated muscle activator of Rho signalling (STARS) is a molecular pathway that is essential to skeletal muscle adaptation and function via the regulation of SRF signalling. Here, we show for the first time that STARS signalling is downregulated in older when

compared to younger human muscle, although STARS regulation following an acute exercise bout is not age dependent. In addition, we identify that miR-628-5p is a resistance exercise responsive miRNA that directly binds the STARS 3'UTR to reduce its transcription *in vitro*.

### Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

**Figure S1.** PPIA gene expression levels in skeletal muscle from young and older subjects pre- and post-exercise.

**Figure S2.** MiR-9, miR-133a, miR-150 and miR-206 expression levels in skeletal muscle from young and older subjects pre- and post-exercise.

**Figure S3.** Predicted binding sites for miR-539-5p, miR-520g-3p and miR-628-5p on human STARS 3'UTR.

**Table S1.** Additional primers used for the Luciferase reporter assay.