Follistatin: A Novel Therapeutic for the Improvement of Muscle Regeneration


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ABSTRACT

Follistatin (FST) is a member of the tissue growth factor β family and is a secreted glycoprotein that antagonizes many members of the family, including activin A, growth differentiation factor 11, and myostatin. The objective of this study was to explore the use of an engineered follistatin therapeutic created by fusing FST315 lacking heparin binding activity to the N terminus of a murine IgG1 Fc (FST315-HBS-Fc) as a systemic therapeutic agent in models of muscle injury. Systemic administration of this molecule was found to increase body weight and lean muscle mass after weekly administration in normal mice. Subsequently, we tested this agent in several models of muscle injury, which were chosen based on their severity of damage and their ability to reflect clinical settings. FST315-HBS-Fc treatment proved to be a potent inducer of muscle remodeling and regeneration. FST315-HBS-Fc induced improvements in muscle repair after injury/atrophy by modulating the early inflammatory phase allowing for increased macrophage density, and Pax7-positive cells leading to an accelerated restoration of myofibers and muscle function. Collectively, these data demonstrate the benefits of a therapeutically viable form of FST that can be leveraged as an alternate means of ameliorating muscle regeneration.

Introduction

A multitude of diseases affect skeletal muscle, ranging from direct injury to the soft tissue or nerve supply, chronic inflammation, aging, and cancer. Irrespective of the mode, it results in the same outcome: limited mobility with the comorbid development of fibrosis that is most often seen due to long-term issues with muscle injury/trauma, the current conservative treatment incorporates the minimization of inflammation with limb elevation and local cooling, in conjunction with a regimented physical therapy plan and an adjuvant treatment with nonsteroidal anti-inflammatory drugs. Irrespective of complying with the aforementioned treatment protocol, it can be difficult to achieve complete recovery from injury because of comitant development of fibrosis that is most often seen due to comorbidities associated with metabolic and structural aging.

Myostatin or growth differentiation factor 8 (Gdf8) is a well-studied member of the tissue growth factor β (TGFβ) family that regulates muscle mass through development and postnatally. Gdf8 has been the center of focus in developing therapeutics, which inhibit and neutralize its activity. A variety of methods to accomplish Gdf8 inhibition include the following: specific antibodies which govern the ability of the ligand to interact with its receptor, dominant negative-mimetic proteins, adenoviruses to deliver a propeptide inhibitor, and a receptor decay composed of the ectodomain of Gdf8.
the activin receptor IIB conjugated to the Fc domain of the IgG molecule (Teo et al., 2012).

Another TGFβ superfamily member, follistatin (FST), has also been found to play a significant role in the management of skeletal muscle size and mass (Amthor et al., 2004; Lee, 2007). FST is composed of a 63-residue amino (N)-terminal domain, followed by three successive follistatin domains of 73–75 amino acids termed FSD1, FSD2, and FSD3 (Wang et al., 2000; Cash et al., 2009). There are three reported isoforms that exist: FST288, FST315, and FST300 (or FST303), which are thought to be products of post-translational modification events (Hashimoto et al., 2000; Sidis et al., 2006). FST288 and 315 proteins differ only in their possession of exon 6, which has been shown to influence their interactions with heparin, whereas FST303 is produced by proteolytic processing of the C-terminal tail domain (Sugino et al., 1993). Full-length exon 6 reduces the overall binding to cell surface heparin-sulfated proteoglycans, which is observed with the FST315 isoform, whereas FST288 lacks exon 6 and, therefore, displays greater cell surface affinity (Sidis et al., 2006). Affinity to cell surface receptors helps dictate the general biological actions of FST with FST288 conducting itself more in an autocrine fashion and FST315 (primarily found in circulation) behaving more as an endocrine factor (Bilezikjian et al., 2004; Yuen and Ge, 2004; Kumar, 2005).

FST proteins were found to associate with Gdf8 in the serum and were later demonstrated to antagonize Gdf8-mediated inhibition of myogenesis (Thomas et al., 2000; Hill et al., 2002). FST-transgenic mice produced a robust skeletal muscle hypertrophy phenotype and, when additionally crossed in a Gdf8-null mouse, resulted in a quadrupling effect on muscle (Lee, 2007). This finding indicated the existence of other muscle regulators besides Gdf8 that follistatin can modulate. Activin A has been the logical option for the second player in regulating muscle mass, and recent data from several laboratories would confer this as the best choice (Gilson et al., 2009; Lee et al., 2012).

Finally, the main objective of this study was to test a newly engineered FST biotherapeutic that fuses a heparin-deficient binding form of follistatin 315 to the N terminus of a murine IgG1 Fc (FST315-ΔHBS-Fc) (Sidis et al., 2005; Datta-Mannan et al., 2013) in multiple models of muscle injury. Our results clearly demonstrate the viability of a systemically administered form of FST that can increase muscle mass, facilitate muscle repair, and restore muscle function in multiple models of muscle injury. Combining FST’s effects on inflammation and pro-regenerative capabilities makes it a practical option for the treatment of muscle diseases where injury is associated.

Materials and Methods

Animal Care and Use

All mouse experiments were performed with the approval of Eli Lilly and Company’s Institutional Animal Care and Use Committee and are in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals.

For all studies described here, 10-week-old C57BL/6 female and male mice were used (Harlan, Indianapolis, IN). Animals were housed in a room with controlled temperature (22 ± 2°C) and a 12:12-hour light-dark cycle (lights on at 6:00 AM) with ad libitum access to food (TD 5001 with 0.95% calcium and 0.67% phosphorus; Teklad, Madison, WI) and water.

In Vivo Electroporation

FST plasmids were constructed by inserting the cDNAs into the cytomegalovirus/actin/globin expression vector (Invivogen, San Diego, CA). DNA for all in vivo experiments was prepared using the ENDO-Free Maxi prep kit (Qiagen, Valencia, CA). DNA was eluted into physiological saline at a concentration of 0.5 μg/μl. Mice legs were shaved and then percutaneously injected with 25 μg (0.05 ml) of cDNA into the gastrocnemius muscle using an insulin syringe. Shortly following the injection of cDNA (~20–30 seconds), four pulses of 160 V/cm for 0.1-ms duration at 100-ms intervals were delivered transcutaneously to the DNA-injected limb at a rate of one pulse per second with a BTX 830M electroporator (model no. 8300; Harvard Apparatus, Holliston, MA) utilizing gene calipers.

In Vivo Injury/Immobilization Models

Cardiotoxin Injury. Cardiotoxin injury was induced similar to what was described by Garry et al. (2000), with slight modifications. Muscle injury was induced by a 100-μl injection of a 10 μM cardiotxin (CTX) solution (cardiotxin 1 from Naja naja atra, part C3987; Sigma-Aldrich, St. Louis, MO) into the right gastrocnemius muscle with a three-point injection technique to fully cover the lateral and medial gastrocnemius. The injected muscles were harvested at various time points following CTX injury. Experiments were performed with each study incorporating an uninjured (no CTX or treatment) control group as a reference.

Cardiotoxin Injury/Hind Limb Immobilization. Lower limb muscles were injured using the aforementioned protocol. Following the CTX injections, mice were subjected to hind limb immobilization using Vet-Lite casting (Jorgensen Laboratories, Loveland, CO). Animals were placed in a plantar-flexed state to allow for maximal atrophy of the gastrocnemius muscle. Animals were maintained in this flexed state for a period of 7 days.

Ovariectomy. Female mice at 8 weeks of age were anesthetized and placed in ventral recumbency. The dorsal midlumbar area was...
shaved and swabbed, and a 2–3-cm dorsal midline skin incision was made halfway between the caudal edges of the rib cage, where a single incision was made into the muscle wall. The ovary and the oviduct were exteriorized through the muscle wall. A hemostat was used to clamp the uterine vasculature between the oviduct and uterus. Each ovary and part of the oviduct were removed with single cuts through the oviducts near the ovary. The ovary on the other side was removed in a similar manner.

**Body Composition**

Lean body mass and fat mass were measured using NMR (Echo Medical Systems, Houston, TX).

**Enzyme-Linked Immunosorbent Assay for Follistatin**

The quantitative determination of human FST concentration was determined using a Human Follistatin Quantikine enzyme-linked immunosorbent assay (ELISA) kit (R&D Systems, Minneapolis, MN). In brief, standards and sample lysates were added to a flat-bottomed 96-well ELISA plate precoated with a monoclonal antibody specific for follistatin. The plate was washed four times, and 400 μL of the enzyme-linked monoclonal antibody specific to follistatin was added to each well. The plate was washed an additional four times and then one additional time to remove any unbound antibody-enzyme reagent. Substrate was added and incubated for 30 minutes, and then plates were read at 450 nm on a microplate reader.

**Histology and Immunohistochemistry**

Muscle tissue was evaluated using H&E and immunolabeled using antiserum F4/80 clone BM8 (eBioscience, San Diego, CA) at 0.5 μg/ml or anti-Pax7 (0.1 μg/ml) (Sigma-Aldrich). Fiber diameter was analyzed in H&E-stained gastrocnemius muscle sections using Aperio ImageScope software (Viata, CA). For each muscle, the distribution of the fiber diameter was calculated by analyzing 100–150 myofibers. Images were acquired using digital slide scanning (ScanScope XT; Aperio).

**Gene Expression Analysis**

RNA was extracted from isolated injured and uninjured skeletal muscles using TRIzol reagent (Life Technologies, Grand Island, NY). Total RNAs were reverse transcribed using the High Capacity cDNA Archive Kit (Applied Biosystems, Foster City, CA). All cDNAs were assayed for genes of interest using TaqMan Gene Expression Analysis (Applied Biosystems, Carlsbad, CA) and the Assay-On-Demand primer/probe set (Life Technologies). Gene of interest mRNA levels were quantitated by determining the cycle number at which amplification detection threshold was achieved. Real-time polymerase chain reactions (PCR) were performed in 20-μl reactions according to the manufacturer’s guidelines. Samples were subjected to quantitative PCR using the ABI 7900HT real-time PCR system (Life Technologies). After normalization to the housekeeping gene (GAPDH) or ribosomal protein [large, P0 (36B4)] for the injury/immobilization, the expression of interest was normalized to the housekeeping gene (GAPDH) or ribosomal protein [large, P0 (36B4)] for the injury/immobilization. The data were analyzed with slight modifications. Seven days after electroporation, muscles were harvested to verify that FST gene expression was being achieved. Figure 1 (A and B) shows day 7 quantification of both RNA and protein (of FST315 from the electroporated muscles). Gene expression was approximately 13-fold higher, whereas protein expression obtained by ELISA was approximately 4-fold higher than empty vector.

**Results**

Native FST288 Promotes Slightly Greater Muscle Anabolic Effects than FST315. The first goal was to examine the consequence of local overexpression of the two native FST isoforms (FST288 and FST315) and one engineered isoform that has been relieved of its heparin binding capability (FST288-HBS). Removal of heparin binding activity in FST288 was facilitated by replacing the native HBS found in its FSD1 domain with that of the homologous sequence in follistatin-like 3 as initially described by Sidis et al. (2005). Female C57BL/6 mice were injected with 25 μg of the aforementioned FST constructs in the gastrocnemius and then subjected to electroperoration similar to the methods produced by Kawai et al. (2006) and Yin and Tang (2001), but with slight modifications. Seven days after electroporation, muscles were harvested to verify that FST gene expression was being achieved. Figure 1 (A and B) shows day 7 quantification (both RNA and protein) of FST315 from the electroporated muscles. Gene expression was approximately 13-fold higher, whereas protein expression obtained by ELISA was approximately 4-fold higher than empty vector.

Once overexpression was successfully achieved, the ensuing experiments were designed to compare and contrast the anabolic effects of the two FST isoforms in adult mice. Female C57BL/6 mice were electroporated with two rounds (day 0 and day 10) of each construct to sustain expression over a longer duration to elicit a more robust phenotype. On day 24, muscles were excised to evaluate changes in muscle mass. Similar to the studies carried out by Gilson et al. (2009), all of the FST-transduced muscles produced substantial increases in muscle wet weights. Gross observation of the excised gastrocnemius in FST groups clearly demonstrated a robust increase in mass relative to the empty vector control–treated animals (Fig. 1C). FST288 increased muscle mass 37.5%, whereas FST315 increased muscle mass 23.7% (Fig. 1D).

Altering the HBS region of FST288 (FST288-DHBS) significantly reduced the local activity of the protein, resulting in a 12.3% increase in muscle mass. To better understand the...
consequence of local FST overexpression, histopathological analysis was performed on muscles harvested on day 24 to assess changes and distribution in myofiber size (Fig. 1E). This analysis revealed a significant increase in myofiber diameter with FST overexpression reflecting overall hypertrophy (Fig. 1F). These data also demonstrate that FST288 overexpression significantly increases myofiber size even when compared with FST315, inferring that the high cell surface affinity of FST288 may lead to a more pronounced local effect in muscle anabolism.

Local Delivery of FST288 and 315 Rapidly Improves Muscle Repair in CTX Muscle Injury Whereas Systemic Delivery Does Not. To investigate a potential benefit of FST administration in muscle regeneration, gastrocnemius muscles were subjected to CTX injury similar to what was described by Garry et al. (2000), with slight modifications. CTX snake venom was chosen as a model because of its ability to recapitulate the specific pathologies observed in muscle injury such as trauma and surgery—namely, inflammation, tissue necrosis, macrophage infiltration, and satellite cell

Fig. 1. Follistatin increases muscle mass in postnatal mice. Gastrocnemii muscles of female C57BL/6 mice were electroporated with DNA constructs containing one of the following cDNAs: FST315, FST288, FST288-ΔHBS, or empty vector (cytomegalovirus/actin/globin). Gastrocnemius muscle was collected 7 days after the first injection to assess muscle gene expression (normalized to GAPDH) (A) and protein levels of FST315 (B). (C) Morphology of excised FST315 electroporated gastrocnemius muscles 24 days following electroporation. (D) Mice were electroporated with empty vector, FST315, FST288, or FST288-ΔHBS, and gastrocnemius muscle mass (GW) was assessed 24 days after the initial injection. (E) Representative H&E cross-sectional images of myofibers from electroporated gastrocnemius muscle from day 24. (F) Fiber diameter of the electroporated gastrocnemius and the frequency distribution of corresponding fibers (black: empty vector; light gray: FST315; dark gray: FST288). *P < 0.05, FST group versus empty vector control (Dunnett’s one-way ANOVA).
activation. One hour prior to muscle injury, mice were administered a local 0.5 mg/kg per day i.m. or 5 mg/kg per day s.c. injection of FST288 or FST315. The treatments continued for a period of 7 days to assess the regenerative effects of both local and systemically delivered FST. On the seventh day of treatment, muscles were excised, and mass was measured. Local administration of the two FST isoforms produced a significant increase in gastrocnemius wet weight (19.2% FST288 and 9.2% FST315, or 99.5% and 103% of the contralateral control, respectively) and was ineffective when systemically delivered (Fig. 2). This was not surprising given the relatively small size of FST and its capability of binding heparin, leading to a rapid clearance of the molecule. Removal of the heparin binding sequence also had no effect when systemically delivered, demonstrating that FST’s size is the main factor in clearance of the molecule (data not shown). We predicted, based on existing data, that FST would indeed diminish the degeneration that is coupled with injury; however, what was unanticipated was FST’s ability to promote rapid repair in the injured muscle in such a short time frame (Zhu et al., 2011).

**Systemic Delivery of a Re-engineered FST315 Leads to Significant Increases in Lean Body Mass in Normal Male Mice.** The next objective was to explore the therapeutic use of a newly engineered FST molecule. FST288, with its high-cell surface interaction capabilities, poor protein expression, and purification attributes, was determined unsuitable for further development; therefore, FST315 was chosen for continued therapeutic development (Datta-Mannan et al., 2013). To improve the systemic exposure characteristics of FST315, additional modifications were performed to increase the size and reduce its cell surface interactions by removal of...
the HBS domain found in follistatin domain 1 (FST315-ΔHBS) (Sidis et al., 2005). FST315-ΔHBS was then fused to a murine IgG1 Fc which aided in increasing the molecular mass of the protein from 28 to approximately 128 kDa, allowing circumvention of the renal clearance mechanism along with increasing the FcRn recycling attributes (Roopenian and Akilesh, 2007). Ultimately, these modifications significantly improved FST315-ΔHBS-Fc exposure (area under the curve) and half-life (~200- and ~30-fold, respectively), enabling systemic delivery of the molecule (Datta-Mannan et al., 2013).

To test the capability of the newly engineered biotherapeutic to produce gains in muscle, we administered the molecule in two different regimens [low-frequency once weekly dose (Q7D) and high-frequency every other day dose (Q2D)] at 10 and 30 mg/kg to male C57BL/6 mice. Studies were conducted for a period of 2 weeks to inquire changes in overall lean body mass (LBM) and individual muscle mass. Weekly dosing generated only modest increases in lean body mass (Fig. 3A), whereas the more frequent (Q2D) treatment regimen dramatically enhanced LBM and muscle mass endpoints as shown in Fig. 3B.

**Systemic Delivery of a Re-engineered Follistatin (FST315-ΔHBS-Fc) in a CTX Model of Muscle Injury.** A time-course study was performed using the newly designed FST315-ΔHBS-Fc to assess its ability to promote muscle repair in the CTX injury model. FST315-ΔHBS-Fc was administered at 10 mg/kg per Q2D for 14 days following muscle injury. FST315-ΔHBS-Fc treatment significantly attenuated the day 1 increase in gastrocnemius bundle muscle

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**Fig. 3.** Systemic delivery of FST315-ΔHBS-Fc protein increases muscle mass endpoints. Male C57BL/6 mice were administered either a low-frequency (Q7D) (A) or high-frequency (Q2D) (B) dose of FST315-ΔHBS-Fc. Gastrocnemius (GW) and quadriceps wet weight (QW) along with LBM were measured 2 weeks following the first administered dose. *P ≤ 0.05, drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).
wet weight (gastrocnemius, plantaris, and soleus) that was observed during the inflammatory phase shortly after injury (Fig. 4A). As early as 5 days of FST315-ΔHBS-Fc treatment, significant gains in body weight (8.8%) were already observed when compared with vehicle IgG (Supplemental Fig. 1). Finally, by day 14, the injured gastrocnemius wet weight was 9.4% greater than the uninjured control (Fig. 4A).

Histologic analysis (H&E) was performed to assess qualitative changes in myocellular structure at critical time points of repair and regeneration. By day 9, histologic evidence of accelerated repair was clearly present, demonstrating differences between FST315-ΔHBS-Fc and vehicle IgG. The vehicle IgG group was found to have a greater presence of myocellular degeneration and monocytic infiltration. The FST315-ΔHBS-Fc–treated groups exhibited traits of accelerated myofiber regeneration as evidenced by the increased presence of centronucleated fibers (Fig. 4B). Regenerating myofiber size in the FST315-ΔHBS-Fc group tended to be larger when compared with the vehicle IgG group on day 9 and became strikingly evident by day 14 when regenerating myofiber diameter was found to be significantly increased (Fig. 4C).

The increased muscle mass observed with 14 days of FST315-ΔHBS-Fc treatment in the context of injury was found to translate into improvements in various aspects of muscle function as determined by in situ contractile assessments (Fig. 4D). Maximum tetanic force was significantly

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**Fig. 4.** Systemic administration of FST315-ΔHBS-Fc (time course) improves muscle repair. (A) Mice received 10 mg/kg FST315-ΔHBS-Fc every other day for a period of 14 days. A time course was performed to monitor the early and late-phase changes in gastrocnemius bundle (including plantaris and soleus) muscle mass (GW). (B) Histology on day 9 and day 14 (black arrows indicating centronucleated fibers) demonstrating the increase in the presence of centronucleated fibers on day 9, and (C) fiber diameter and fiber diameter frequency distribution of vehicle IgG and FST-treated mice (black bars: vehicle IgG; gray bars: FST). (D) In situ muscle function on day 14 (black open squares: uninjured; red squares: vehicle CTX; green open triangles: FST-CTX). (E) Additional contractility measurements from day 14. Data for the in situ measurements are expressed as means ± S.E.M. (n = 8 mice/group). *P ≤ 0.05, drug-treated group versus IgG-treated group or IgG-treated group versus uninjured/nontreated group (Dunnett’s one-way ANOVA).
improved with FST315-ΔHBS-Fc and was comparable to the uninjured (nontreated) group. Increases in specific force were also observed, albeit not as robust, demonstrating the muscles’ ability to efficiently produce stronger contractions per calculated physiologic CSA. FST315-ΔHBS-Fc also resulted in significant improvements in maximum integration, indicating an ability of the muscle to sustain contractions for longer durations (Fig. 4E). CTX injection significantly decreased maximum force and twitch tension, and FST treatment significantly improved it over the vehicle group (Fig. 4E). Maximum force, upon normalization to gastrocnemius bundle wet weight, produced only a slight trend in normalized force (~10%); however, when normalized to overall body mass, a significant 37% increase was found (Supplemental Fig. 2, A and B). Collectively, this improvement in maximum and specific force on day 14 upon FST315-ΔHBS-Fc is an important finding and validates a key outcome that delay in speed of muscle repair may lead to functional deficiency and is typically not measured in animal studies.

Next, we investigated the presence of macrophages in the time course. F4/80, which is a highly glycosylated proteoglycan extracellular antigen found on mature murine macrophages, was measured to evaluate the presence of macrophages in muscle sections (Haidl and Jefferies, 1996). F4/80 staining revealed an early increase in the density of F4/80-positive cells in FST315-ΔHBS-Fc–treated samples on day 3, which persisted until day 14 (Fig. 5A). These data indicate that the FST315-ΔHBS-Fc alteration of day 1 inflammation may affect infiltration or proliferation of macrophages.

Paired box protein Pax7 belongs to a family of genes that encode for transcription factors and in this case play a distinct role in specification of myogenic satellite cells (Seale et al., 2000). Satellite cells are activated upon injury and are the key drivers in muscle regeneration. Immunohistochemistry was performed on tissue sections from CTX time course samples to measure changes in Pax7 protein expression. Pax7-positive cells were found to be more abundant on day 7 and day 9 (Fig. 5B; Supplemental Fig. 3) compared with vehicle IgG1-treated animals (Fig. 5B). These histopathological observations help corroborate the increases in mass changes seen with FST315-ΔHBS-Fc treatment.

To explore the molecular basis of FST315-ΔHBS-Fc’s ability to improve muscle recovery, we explored several genes that are associated with critical aspects of the regeneration process. First off, we measured numerous genes associated with the inflammatory process and the polarized state of macrophages in an attempt to understand the early attenuation in wet weight gain seen with FST treatment. Of these...
genes explored, three genes in particular were regulated, providing a potential mechanism of action. Prostaglandin-endoperoxide synthase 2 (Cox2) and chemokine receptor 7 (CCR7) were both induced following injury and further potentiated with FST treatment (Fig. 6A). This is intriguing because both of these genes have been shown to be essential in cell adhesion, proliferation, and facilitating repair (Shen et al., 2006; Sasaki et al., 2008). Further investigation

**Fig. 4.** Continued

![Graphs showing tension-time integral and max tetanic force](image)

**Fig. 5.** FST315-ΔHBS-Fc treatment increases macrophage density and markers of muscle precursor cells. Gastrocnemius muscle samples collected from 3, 5, and 9 days following CTX injury. (A) Macrophage-F4/80-positive cell quantifications and their representative sections on days 3 and 5 at 20× and 10×, respectively. (B) Pax7 immunohistochemistry (black arrows indicate Pax7-positive cells on day 9). *P ≤ 0.05, drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).
revealed that, on day 3, resistin-like α was also increased in the FST-treated group (Fig. 6A), demonstrating another alteration in early inflammatory modulators.

Later time points were explored to identify genes affecting the restoration of tissue. In doing so, FST treatment was found to significantly reduce connective tissue growth factor...
CTGF along with TGFβ is a profibrotic maker that is tightly linked to diseases such as Duchenne muscular dystrophy (Sun et al., 2008). Aberrant expression of CTGF has been shown to induce phenotypes of fibrosis. In our studies, when compared with vehicle IgG control, FST significantly downregulated CTGF expression on day 5 following CTX injury (Fig. 6B). NOS1 or nNOS was measured due to its expression and capability in regulating satellite cell differentiation and fusion (Wozniak and Anderson, 2007). Five days after injury, FST-increased nNOS expression was approximately 2.4-fold higher than vehicle IgG–treated animals (Fig. 6B).

In addition to gene changes, we also wanted to explore chemokine and cytokine protein expression 2 days after injury to better understand the effects of FST315-ΔHBS-Fc on muscle inflammation. We chose 2 days (postinjury) due to the increase in Smad2/3 protein induced by CTX injury that was attenuated with FST treatment (Supplemental Fig. 4). Because of the uncertainty regarding which cytokines may be altered with FST treatment, we used the mouse cytokine/chemokine magnetic bead panel to measure a variety of them (Millipore). This panel allowed us to explore 32 proteins that are related to inflammation. We found that FST reduced both interleukin 17a (IL17a) and IL13 in the context of CTX-induced injury (Fig. 6C; Supplemental Fig. 5).

**FST315-ΔHBS-Fc Delivered Systemically Improves Muscle Mass in a Clinically Relevant Model of Muscle Disuse and Injury (CTX+Hindlimb Immobilization).** To further test the potential therapeutic utility of FST315-ΔHBS-Fc, a study was performed in a more clinically relevant model, which merges CTX injury and immobilization into one. In this scenario, mice were injured using the standard CTX injury protocol and then immediately subjected to immobilization in a plantar flexed position using a 2-mm Vet-Lite cast material (Jorgensen Laboratories). We have shown that combining these two models extends the inflammatory response, with a concomitant increase in the degenerative phase that further delays muscle repair. To maintain clinical relevance, treatment commenced 2 hours after the mice had recovered from anesthesia to better reflect a muscle trauma/treatment setting. Experiments with FST315-ΔHBS-Fc in this model focused on two dosing regimens, everyday dosing (QD) and Q2D at both 10 and 30 mg/kg. At the termination of the study (14 days) body weights had increased 21% in the QD 10 mg/kg group and 14% in the QD 30 mg/kg group compared with vehicle IgG-treated animals (Fig. 7A). The injured and immobilized gastrocnemius (gastrocnemius only) muscles lost approximately 29.7% mass when compared with the unaffected muscle as a result of injury and immobilization. FST-treated muscles increased gastrocnemius mass anywhere between 27% and 36% and in most cases above that of the control (untreated) muscles (Fig. 7B). It was also noted that the immobilized quadriceps atrophied 9.6% and were completely protected with FST treatment (Fig. 7B). Subsequent to these findings, we wanted to look into the rapidity with which FST treatment can recover muscle mass in the CTX-injured and immobilized model.

A time course was performed to investigate the temporal regulation of regeneration with FST-treated mice in the

Fig. 7. Therapeutic administration of FST315-ΔHBS-Fc shows robust efficacy with daily and every other day dosing in a more severe model of injury and immobilization. (A) FST315-ΔHBS-Fc was administered approximately 3 hours after the animals were injured and immobilized. Animals received either daily (QD) or Q2D treatments, and body weight (BW) was collected on day 14. (B) Muscle wet weights were collected on injured immobilized gastrocnemius (GW) and immobilized quadriceps (QW). *P ≤ 0.05, drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).
context of injury/immobilization. Based on the previous results, a high-frequency treatment regimen of 30 mg/kg per Q2D FST315-ΔHBS-Fc was chosen. We also included a less frequent Q7D dose to query the lowest amount required for efficacy. Because of the severity of the model, we chose the higher 30 mg/kg dose of FST. Mice were injured and then immobilized, and muscles were collected on days 1, 3, 7, 10, and 14 to evaluate changes in muscle mass over the 2-week period. In this study, we found that, by day 10, the FST315-ΔHBS-Fc Q2D group had already increased their body weight by 14%, and it continued to increase up to 30% by the termination of the study (Fig. 8A). The less frequent FST Q7D–treated group experienced a 6.7% increase in overall body weight. Total lean body mass acquired from QNMR readings on days 9 and 14 confirmed that the gain in body weight observed was indeed bona fide fat-free lean muscle (Fig. 8B). In regards to the effects on injured/immobilized muscle tissue, the FST315-ΔHBS-Fc Q2D dose significantly increased injured immobilized muscle mass as early as day 10 and exhibited signs of hypertrophy by day 14 (Fig. 8C).

Gene expression analysis was also performed on the time course to correlate the increased mass findings to gene signatures reflective of repair. α-Cardiac actin (Actc1) expression has been shown to be regulated during muscle regeneration following trauma from pathologic diseases that appears characteristic of activated satellite cells and regenerating myofibers (Dennis et al., 2008). On day 10, Actc1 was significantly increased with both the high- and low-frequency doses of FST, whereas on day 14 it was only significant with the high-frequency dose, producing a 3.7-fold increase (Fig. 9A). Myosin heavy polypeptide 4, a late or structural marker in myogenesis, was also measured and found to be significantly increased in only the high-dose group on day 14 (Fig. 9A).

Muscle samples were taken from day 14 to examine histologic changes with FST315-ΔHBS-Fc treatment. Representative cross-sections and longitudinal sections from FST-treated muscles show an overall reduction in the mononuclear cell staining along with significantly larger centronucleated fiber diameter when compared with the vehicle IgG control (Fig. 9, B and C).
significant muscle recovery observed by both mass and histologic observations, we wanted to ensure this translated into qualitative improvements in muscle function. In situ skeletal muscle contractile properties of the gastrocnemius bundle were assessed in the FST315-ΔHBS-Fc treatment group. Similar experiments were conducted as before and were extended to 21 days of treatment (1 week of immobilization and 2 weeks of reambulation). Maximum tetanic force and absolute twitch tension were found to be significantly improved even with weekly FST315-ΔHBS-Fc treatment when compared with the vehicle IgG group. Force-frequency relationships were also calculated to show a significant increase in the functionality of muscle across multiple frequencies (Fig. 9D).

As a final point, we wanted to extend the amount of damage as well as introduce variables that would better correspond to a potential patient. Elderly patients are typically more susceptible to damage and tend to have a body composition high in fat. In addition, since our injury studies have focused primarily on females, we wanted to recapitulate some of the key aspects of menopausal women where increases in FSH are seen to compensate for a loss of estrogen hormones (Rodin et al., 1990). In doing so, female mice were ovariectomized for an extended period of time to allow for a body compositional switch and a reduction in insulin sensitivity, potentially making it more difficult for mice to repair their injured immobilized muscles (Jansson et al., 2006; Vieira Potter et al., 2012). Experiments were performed in treatment mode...
(2 hours after injury) using a dose titration and carried out for a period of 2 weeks. Similar to the previous experiments, FST treatment resulted in a dose-dependent increase in injured-immobilized gastrocnemius wet weight with 14 days of treatment (Fig. 10). In the two high-dose groups of FST, injured-immobilized gastrocnemius wet weights were back to normal compared with uninjured loaded control (indicated by the dotted line). Additionally, serum FSH levels were measured in the vehicle and high-dose FST groups. The re-engineered FST was shown to significantly decrease the elevated FSH levels seen in these mice as a result of ovariectomy (Supplemental Fig. 6).

**Discussion**

In this report, the primary objective was to investigate the beneficial application of a novel FST therapeutic in ameliorating the effects of muscle damage in a variety of clinically relevant injury models. We believe that FST’s unique ability in neutralizing multiple members of the TGFβ family results in an improved ability to augment muscle repair more so than merely inhibiting one member alone. Ultimately, we found that FST possesses attributes beyond that of a simple growth factor, increasing myofiber size. We were able to demonstrate that these additional attributes include the ability to modify
the inflammatory response, potentially altering macrophage density/polarity to bolster satellite cell activation and recruitment. This concurrent alteration of inflammation and macrophage density observed with FST treatment may promote necrotic debris clearance and sustain myogenesis, leading to a robust increase in muscle mass and function. Our studies took the next step in determining the therapeutic viability of FST by using a newly engineered protein that afforded us the means of systemic delivery in a treatment paradigm. These data are the first of their kind reflecting a truer clinical scenario which has not been limited to preventative or prophylactic treatments.

Follistatin, originally known as an activin-binding protein, interacts with several members of the TGFβ family with varying affinities such as GDF11, bone morphogenic factor 2/7, and activins A and B. It has been debated over the years which members of the TGFβ family are inhibited by FST and contribute to its robust increase in skeletal muscle mass. Activin A recently has been established as an inducer of muscle atrophy when exclusively overexpressed in muscle via electroporation and through overexpression of activin A tumors (Gilson et al., 2009; Zhou et al., 2010). One group reengineered an FST variant by removing domain II (FSD2), rendering the molecule incapable of binding activin A (Gilson et al., 2009). Their findings uncovered a diminution in the increase in muscle mass, producing a similar growth response that is observed with myostatin inhibition. It has even been shown in humans that serum concentrations of activin A or the bioavailability increase in an age-related progressive manner between 20 and 50 years of age, maxing out in males between 70 and 90 years of age and in females at perimenopause (loss of FST), possibly contributing to the onset or progression of sarcopenia in both sexes (Loria et al., 2017; Reame et al., 2007). Prolonged inflammation can have a deleterious effect on skeletal muscle repair by impeding proper satellite stem cell activation and activating myofibroblast differentiation, both of which result in scar formation (Mann et al., 2011). Nevertheless, it is necessary to maintain some level of inflammation as it is an obligatory cue to initiate repair through satellite cell activation and expansion. This is evidenced by the early regulation of several genes reflective of inflammation and activated macrophages. Potentiated expression of resistin-like α and CCR7 early in regeneration may help expedite the activation of macrophages as macrophage activation has been described as playing a key role in tissue regeneration (Munitz et al., 2008). These findings were validated by the heightened density of F4/80-positive cells found in the epimysium on days 3 and 5 post injury. This increase in macrophage infiltration has also been observed with gdf8 inhibition in a similar model of muscle injury, inferring a common mechanism. One hypothesis could be that infiltration of mononuclear cells may be transiently more inflammatory (more M1-CCR7), thus making a quick transition to the M2-promyogenic macrophage. Activin A also plays a role in establishing polarity of macrophages, supporting a proinflammatory phenotype identified by EGLN3 (egl-9 family hypoxia-inducible factor 3) expression and inhibition of the attainment of an anti-inflammatory macrophage (Sierra-Filardi et al., 2011). In our CTX time course studies, EGLN3 expression led to the rapid repair in recovery. TGFβ1, myostatin, and activin A have all been described as potent inducers of scar formation; however, we have been unable to show direct interactions between FST and TGFβ1. One piece of data that corroborates these antifibrotic effects is the reduction of CTGF on day 5 by FST treatment. CTGF has been known to play a direct role in contributing to muscle dystrophy, and has been shown to be regulated by activin A in hepatocytes (Gressner et al., 2008; Morales et al., 2011). In future experiments, these gene changes could be monitored in other models of fibrosis where FST is tested.

The data described in this article reveal a mechanism that helps elucidate the rapidity with which FST can promote muscle regeneration and recovery. Follistatin is able to accomplish accelerated muscle restoration not only by leveraging the regenerative effects of myostatin inhibition but potentially through modulating inflammation and pro-reparative aspects via activin A inhibition (Fumagalli et al., 2007; Jones et al., 2007). Prolonged inflammation can have a deleterious effect on skeletal muscle repair by impeding proper satellite stem cell activation and activating myofibroblast differentiation, both of which result in scar formation (Mann et al., 2011). Nevertheless, it is necessary to maintain some level of inflammation as it is an obligatory cue to initiate repair through satellite cell activation and expansion. This is evidenced by the early regulation of several genes reflective of inflammation and activated macrophages. Potentiated expression of resistin-like α and CCR7 early in regeneration may help expedite the activation of macrophages as macrophage activation has been described as playing a key role in tissue regeneration (Munitz et al., 2008). These findings were validated by the heightened density of F4/80-positive cells found in the epimysium on days 3 and 5 post injury. This increase in macrophage infiltration has also been observed with gdf8 inhibition in a similar model of muscle injury, inferring a common mechanism. One hypothesis could be that infiltration of mononuclear cells may be transiently more inflammatory (more M1-CCR7), thus making a quick transition to the M2-promyogenic macrophage. Activin A also plays a role in establishing polarity of macrophages, supporting a proinflammatory phenotype identified by EGLN3 (egl-9 family hypoxia-inducible factor 3) expression and inhibition of the attainment of an anti-inflammatory macrophage (Sierra-Filardi et al., 2011). In our CTX time course studies, EGLN3 expression led to the rapid repair in recovery. TGFβ1, myostatin, and activin A have all been described as potent inducers of scar formation; however, we have been unable to show direct interactions between FST and TGFβ1. One piece of data that corroborates these antifibrotic effects is the reduction of CTGF on day 5 by FST treatment. CTGF has been known to play a direct role in contributing to muscle dystrophy, and has been shown to be regulated by activin A in hepatocytes (Gressner et al., 2008; Morales et al., 2011). In future experiments, these gene changes could be monitored in other models of fibrosis where FST is tested.

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was downregulated on day 1; however, this was not significant \((P = 0.09)\). The increase in infiltration and rapid switch of macrophages to M2 may facilitate muscle repair by enhanced activation/proliferation of satellite cells, debris clearance, and growth in injured muscles (Arnold et al., 2007). In addition, we were able to identify trends in gene expression of CD163 on days 1 and 3; however, significance was not achieved. These gene changes combined with pathology have shown an alteration in the macrophage density, indicating a potential M2 anti-inflammatory, promyogenic state switch.

A potential switch in macrophage polarity could in turn activate quiescent satellite cells, promoting efficient recruitment to the injured area. Cox2 and nNOS expression may represent gene profiles reflecting the enhancement in satellite cell recruitment and fusion which was substantiated by increased Pax7-positive cells. Early in repair, Cox2 has been shown to be a critical component in the repair process as knockouts are severely compromised (Shen et al., 2006). This may suggest a mechanism in which the muscle may be better prepared for additional insult(s) by fully replenishing its satellite cell reservoir. Finally, we are pursuing the potential involvement of FST-mediated blockade of activin A in regulating intracellular calcium levels and recycling, which could augment cross-bridging of myofilaments that ultimately results in enhanced force generation. Evidence supporting this has been described by Funaba et al. (2003), showing that activin A is increased by rising levels of cytosolic calcium levels in basophilic mast cells. If this mechanism holds true in muscle cells, FST could then reduce the ongoing damaging effects of calcium in injured muscles by neutralizing the production of activin A.

Treatment with FST was found to inhibit IL17a and IL3 cytokine expression. IL17a is described as a proinflammatory cytokine that is produced by a subset of T cells known as helper T 17 cells (Torchinsky and Blander, 2010). IL17a has been found to be upregulated in Duchenne muscular dystrophy and has been demonstrated to negatively affect myoblast migration and terminal differentiation (De Pasquale et al., 2012; Kocic et al., 2013). Furthermore, another group has postulated that IL17, which is induced by IL6 and activated by IL23, might have a significant contribution in promoting activation of neutrophils and ensuing muscle damage following prolonged endurance exercise (Sugama et al., 2012). Future studies would include the exploration of additional days and the effect FST may have on the chemokine/cytokine profile throughout regeneration.

Currently, ongoing efforts are focused either on myostatin inhibitors or decoy receptors (ACVR1IB-Fc). Gdf8 inhibitors may be faced with limited efficacy in conditions where there are concomitant increases in activin A or persistent inflammation and/or scarring. The activin receptor IIB decoy therapeutic is a weak activin A inhibitor, and has already faced many issues in the clinic with patient safety as a result of neutralizing many members of the TGFβ family.

In summary, these findings support a role for FST in its ability to improve muscle repair and recovery by inhibiting multiple members of the TGFβ superfamily. Our data offer a new alternative for the development of biotherapeutics for indications in which skeletal muscle injury and immobilization are present. Our studies provide the first evidence demonstrating a treatment dosing paradigm of follistatin that would mimic a real-life scenario: an elderly patient (low muscle and high fat mass) suffering traumatic injury to a lower limb (e.g., hip fracture) and within an hour or so arriving at the emergency or critical care unit and having access to regenerative therapeutics. This situation would not be amenable to adenosyl delivery of a molecule due to its long-term, uncontrolled expression and lag time in which it takes to reach efficacious levels. In certain unique situations, exploiting follistatin’s “engineerable” duality could be applied locally for a non–weight-bearing injury or even systemically for patients who would be exposed to long-term immobilization resulting in global atrophy. These are just prime examples illustrating the need to have a molecule(s) that could be delivered as proximal to the injury as possible. This information should encourage the examination of FST or follistatin mimetics for clinical use for muscle injury.

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Authorship Contributions


References


activin neutralizing activity of follistatin isoforms is dependent on their affinity for activin, Cell Signal 12:365–371.


Khan M,引发性 activity of follistatin isoforms is dependent on their affinity for activin, Cell Signal 12:365–371.

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Follistatin: a novel therapeutic for the improvement of muscle regeneration

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SUPPLEMENTAL FIGURE LEGENDS

Supplemental Figure 1: FST treatment increases body weight on day 5 post injury in the CTX model. (A) Mice received 10 mg/kg of FST315-ΔHBS-Fc every other day for 5 days and then body weight was measured. Data are expressed as means ± S.E.M. of 5 mice per group. Significance is indicated *P ≤ 0.05, drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).

Supplemental Figure 2: Force normalized to body and muscle mass from day 14 CTX injury. In situ muscle function was performed on the posterior compartment muscles (gastrocnemius, soleus and plantaris). Follistatin treatment (dark gray) in CTX injury only improved absolute force when normalized to body mass (A) and not to muscle mass (B). Data are expressed as means ± S.E.M. (n=8 mice/group). Significance is indicated *P ≤ 0.05, drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).

Supplemental Figure 3: Pax7 positive cells increased with FST treatment on day 7. Representative sections from Pax7 IHC on day 7 post CTX injury at 20X. Significance is indicated *P ≤ 0.05, drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).

Supplemental Figure 4: FST treatment decreases total Smad 2/3 protein on day 2 post CTX injury. Total Smad2/3 muscle protein levels were measured 2 days following CTX-injury via
ELISA. Data are expressed as means ± S.E.M. of 5 mice per group. Significance is indicated \(*P \leq 0.05\), drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).

**Supplemental Figure 5:** FST treatment decreases IL3 post injury. Day 2 protein expression levels of IL3 in injured gastrocnemius muscle were measured by Luminex multiplexing magnetic bead panel (Millipore) in uninjured, vehicle IgG1 and FST treated mice. Data are expressed as means ± S.E.M. with five mice per group. Significance is indicated \(*P \leq 0.05\), drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).

**Supplemental Figure 6:** FST treatment in ovariectomized female mice decreases FSH. On day 14, FSH levels in ovariectomized female mice were measured to assess a role in pituitary function using the vehicle IgG1 and 30 mg/kg FST groups. Data are expressed as means ± S.E.M. with seven mice per group. Significance is indicated \(*P \leq 0.05\), drug-treated group versus IgG-treated group (Dunnett’s one-way ANOVA).
Supplemental figure 1

![Graph showing BW (grams) comparison between Veh-IgG and FST-Q2D. The graph indicates a statistically significant difference marked by an asterisk (*) on the FST-Q2D group.]

n=7
BW (grams)
Supplemental figure 2

A

B

Normalized Force (N/grams)

0.000 0.005 0.010 0.015 0.020 0.025

Non injured Veh-IgG FST

Normalized Force (N/mg)

0.000 0.001 0.002 0.003 0.004

Non injured Veh-IgG FST
Supplemental figure 3

Veh-IgG  Pax7

FST  Pax7

20x  20x
Supplemental figure 4

Day 2

![Bar graph showing Total Smad 2/3 expression on Day 2 for Non-injured, Veh-IgG, and FST groups.](image)
Supplemental figure 5

Day 2

IL3 (pg/mL)

Day 2

<table>
<thead>
<tr>
<th>Treatment</th>
<th>IL3 (pg/mL)</th>
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<tbody>
<tr>
<td>Non-injured</td>
<td>1.1</td>
</tr>
<tr>
<td>Veh-IgG</td>
<td>1.2</td>
</tr>
<tr>
<td>FST</td>
<td>*</td>
</tr>
</tbody>
</table>

*Significant difference compared to Non-injured
Supplemental figure 6

Day 14

OD (450nm)

Vehicle-Q2D

FST-Q2D

*