Molecular Therapy
Original Article

Functional Rescue of Dystrophin Deficiency in Mice Caused by Frameshift Mutations Using *Campylobacter jejuni* Cas9

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Duchenne muscular dystrophy (DMD) is a fatal, X-linked muscle-wasting disease caused by mutations in the *DMD* gene. In 51% of DMD cases, a reading frame is disrupted because of deletion of several exons. Here, we show that CjCas9 derived from *Campylobacter jejuni* can be used as a gene-editing tool to correct an out-of-frame *Dmd* exon in *Dmd* knockout mice. Herein, we used Cas9 derived from *S. pyogenes* to generate *Dmd* knockout mice with a frameshift mutation in *Dmd* gene. Then, we expressed CjCas9, its single-guide RNA, and the EGFP gene in the *tibialis anterior* muscle of the *Dmd* knockout mice using an all-in-one adeno-associated virus (AAV) vector. CjCas9 cleaved the target site in the *Dmd* gene efficiently *in vivo* and induced small insertions or deletions at the target site. This treatment resulted in conversion of the disrupted *Dmd* reading frame from out of frame to in frame, leading to the expression of dystrophin in the sarcolemma. Importantly, muscle strength was enhanced in the CjCas9-treated muscles, without off-target mutations, indicating high efficiency and specificity of CjCas9. This work suggests that *in vivo DMD* frame correction, mediated by CjCas9, has great potential for the treatment of DMD and other neuromuscular diseases.

INTRODUCTION

Duchenne muscular dystrophy (DMD), an X-linked recessive disorder affecting 1 in 3,500 male births, is caused by nonsense or frameshift mutations in the gene encoding dystrophin, resulting in the absence of this protein in skeletal and cardiac muscles.[1] Dystrophin, an elongated protein localized to the inner face of the sarcolemma, is a key component in the assembly of the dystrophin-glycoprotein complex, which provides a mechanically strong link between the cytoskeleton and the extracellular matrix.[2] Dystrophin-deficient DMD muscle is therefore mechanically destabilized, a primary cause of the myofiber necrosis and muscle wasting associated with this lethal disease.[3]

Conventional therapies are limited to supportive care that partially alleviates signs and symptoms but does not directly target the disease mechanism or reverse the phenotype. Currently ongoing clinical trials include the following gene therapy strategies: dystrophin gene addition therapy using adeno-associated virus (AAV) vectors;[4,5] cell transplantation therapy;[6–8] pharmacological rescue of *DMD* nonsense mutations;[9,10] and exon-skipping strategies to repair the *DMD* transcript reading frame.[11–14] There is currently only one approved drug (eteplirsen) available for DMD using exon-skipping strategy.[15] This approach is limited to specific mutations in addition to the requirement for repetitive administrations. Thus, new approaches are urgently needed.

Genome editing is a powerful method for creating permanent genetic modifications as a corrective treatment strategy for a variety of genetic diseases and as such could provide a means of gene therapy for DMD that would only need to be administered once. In the context of DMD, gene editing has been achieved using programmable endonucleases, designed to specifically target a sequence of choice, to introduce a DNA double-strand break (DSB) in the genome. The *DMD* gene has been repaired either through efficient but error-prone non-homologous end joining (NHEJ)[16] or inefficient but precise homology-directed recombination (HDR) using a donor DNA template.[17]

The power of these approaches has been dramatically increased by the development of the bacterial CRISPR/Cas9 system for correcting specific *DMD* mutations in both *ex vivo* and *in vivo* contexts.[18–25] In these studies, two different bacterial Cas9s have been tested: *Streptococcus pyogenes* Cas9 (SpCas9)[18,21,24] and *Staphylococcus aureus* Cas9 (SaCas9).[21–23] To remove specific DMD-associated mutations, two intron-targeting single-guide RNAs (sgRNAs) together with SpCas9 or SaCas9 have been used to induce multiexon deletions

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in the *DMD* gene in human *DMD* patient cells[26] or single-exon deletions in the *Dmd* gene that harbors nonsense mutation. Both AAV vectors[18,21–23] and adenoviral vectors[24] have been employed to deliver the genome editing machinery *in vivo*. For the larger SpCas9, targeting efficacy was observed when the guide RNAs were delivered separately in a second AAV vector.[23] Due to the respective sizes of their coding sequences, SpCas9 (4.1 kbp) and SaCas9 (3.16 kbp) cannot be packaged into an AAV vector together with a sgRNA and a marker gene, which would allow tracking of delivery and expression *in vivo*. Very recently, the smallest Cas9 ortholog characterized to date (2.95 kb) was identified from *Campylobacter jejuni*[27] and packaged into an all-in-one AAV vector expressing CjCas9, sgRNA, and EGFP.[28] This vector has been successfully delivered into *tibialis anterior* (TA) muscles of C57BL/J wild-type mice, resulting in indel formation at the *Rosa26* locus with no detectable off-target effects up to 32 weeks post-injection.[28] Off-target mutations were rarely observed with CjCas9, partially because it has an extended protospacer-adjacent motif (PAM) (5′-NNNNRYAC-3′) relative to SpCas9 (5′-NGG-3′).

Approximately 51% of DMD patients harbor frameshifting exon deletions rather than point mutations, which are found in 27% of DMD patients based on the Leiden DMD mutation database.[29] Thus, the study was designed to demonstrate that introduction of double-strand breaks into the genome could correct the disrupted reading frame of the *Dmd* gene harboring frame shifting mutations. In this study, we investigated whether NHEJ-based genome editing using AAV-CjCas9 could correct the disrupted *Dmd* reading frame and restore a dystrophin protein expression to support muscle strength. We took advantage of the small size and target specificity of CjCas9 to package in an all-in-one AAV vector. We show here that NHEJ via a single AAV-CjCas9 delivery can repair an out-of-frame *Dmd* exon to in frame sufficiently to restore *Dmd* muscle strength *in vivo*.

RESULTS

Generation of a *Dmd* Knockout Mouse Harboring a Frameshift Mutation

To investigate NHEJ-mediated repair of a disrupted *Dmd* reading frame, we generated a *Dmd* knockout mouse via ribonucleoproteins (RNPs) delivery[30–32] of SpCas9 and a sgRNA targeting exon 23 of the *Dmd* gene (Figure 1A). Several of the resulting offspring displayed targeted mutations in the *Dmd* gene (Figure 1B). Sanger sequencing showed that *Dmd* mutations had occurred in 8 out of 31 offspring; all were heterozygous (Figures 1B and 1C). The male offspring showed no dystrophin protein expression (Figures 1D and 1E) as a result of the SpCas9-mediated frameshift mutation, indicating complete knockout of the *Dmd* gene.

Correction of the *Dmd* Reading Frame by CjCas9-Mediated NHEJ

To investigate whether CjCas9 could restore the *Dmd* reading frame, we used CjCas9 and a 22-nucleotide-specific sgRNA (termed gX_{22} sgRNA, where "g" is an extra guanine nucleotide required for transcription under the control of the U6 promoter, targeting a region upstream of the premature stop codon [PSC] containing a 5′-NNNNGCAC-3′ PAM in *Dmd* exon 23; Figure 2A). The resulting construct was cloned into an all-in-one AAV vector plasmid and transfected in C2C12 myotubes. Indels were induced with a frequency of 25 ± 7.4% (Figure S1).

We next packaged sequences encoding CjCas9 and its sgRNA into a single AAV serotype 9 vector (Figure 2B). This AAV2/9-CjCas9 viral vector was administered via intramuscular injection into the TA muscles of 8-week-old male *Dmd* knockout mice (5×10^{11} vector genomes [vgs] per TA muscle). CjCas9 induced indels with a frequency of 8 ± 0.7% or 3 ± 0.6% in TA muscles of *Dmd* knockout mice harboring either the 1-bp insertion or the 14-bp deletion in exon 23, respectively, 8 weeks post-injection, as assessed by deep sequencing (Figure 2C). 27.2% of these indels caused the correction of the *Dmd* reading frame.

To determine the genome-wide specificity of the CjCas9 nuclease, nuclease-digested whole-genome sequencing (Digenome-seq)[33–35] was used. In parallel, we tested SpCas9 nucleases (recognizing a 5′-NGG-3′ PAM) that were designed to cleave sites that overlapped with the CjCas9 target sites. CjCas9 cleaved 8 off-target sites in the mouse genome, whereas SpCas9 cleaved 105 off-target sites (Figure 2D). Next, we performed targeted deep sequencing in AAV2/9-CjCas9-treated muscles at these potential Digenome-seq-captured 8 off-target sites. No off-target indels were detectably induced at these off-target sites, whereas on-target indels were present with a frequency of 8 ± 0.7% in AAV2/9-CjCas9-treated TA muscles of *Dmd* knockout mice harboring the 1-bp insertion mutation (Figure 2E; Table S1). It showed that the CjCas9 nuclease targeted the *Dmd* gene in skeletal muscles in a highly specific manner, without any detectable off-target effects *in vivo*.

Restoration of Dystrophin Protein Expression that Interacts with nNOS after CjCas9-Mediated Repair of the Reading Frame

Next, we examined whether the repaired *Dmd* reading frame led to dystrophin protein expression. The AAV2/9-CjCas9 delivery resulted in induction of dystrophin expression in TA muscles compared to that in the saline-injected control muscles (Figure 3A). Approximately 39 ± 4% of the fibers were dystrophin positive in the 1-bp insertion-mutation-harboring *Dmd* knockout mice with indel frequencies of 8 ± 0.7%, whereas 28 ± 6% of the fibers were dystrophin positive in the 14-bp deletion-mutation-containing *Dmd* knockout mice with indel frequencies of 3 ± 0.6% (Figure 3B). Dystrophin-positive fibers showed sarcolemmal localization of neuronal nitric oxide synthase (nNOS) (Figure 3A). CjCas9 conjugated with hemagglutinin (HA) tag was detected in the nucleus of dystrophin-positive fibers (Figure 3C). It was also detected at the sarcolemma of dystrophin-positive myofibers, demonstrating the expression of CjCas9 in the fibers (Figure 3C).

Improvement of Muscle Strength in AAV2/9-CjCas9-Treated Muscles

To investigate the ability of the dystrophin protein induced by CjCas9-mediated NHEJ to increase muscle strength, AAV2/9-CjCas9 was

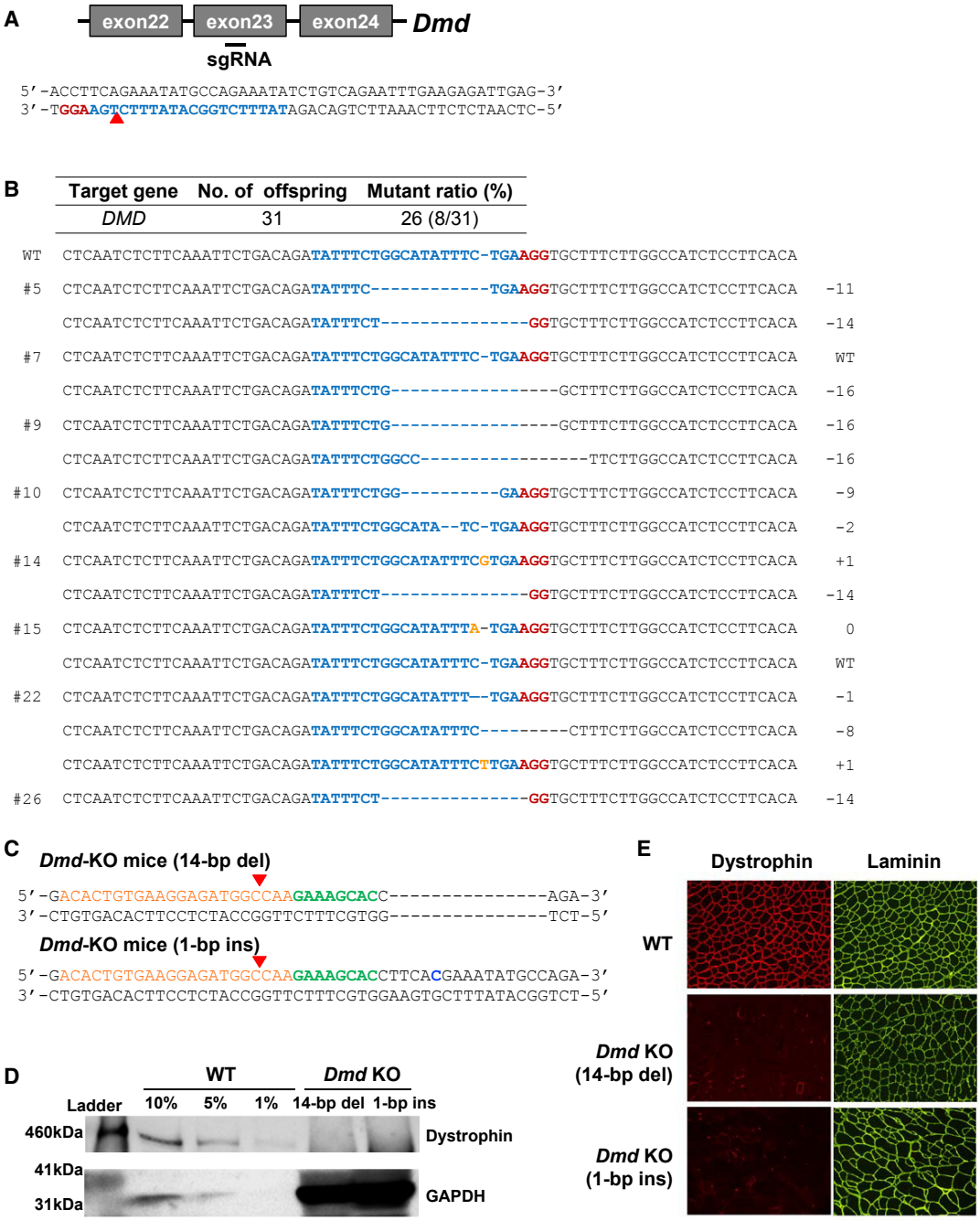

Figure 1. Generation of a *Dmd* Knockout Mouse

(A) SpCas9 target sequence in exon 23 of the murine *Dmd* gene. The PAM sequence of SpCas9 is shown in red and the target sequence in blue. The predicted Cas9 cleavage site is marked by a red arrowhead. (B) Sanger sequencing assay to analyze mutations at the target site is shown. The numbers of offspring obtained after transplant into surrogate mothers and mutants generated are indicated. Inserted nucleotides are shown in yellow. (C) Mutations at the target site in offspring from an F0 mouse (no. 14) cross-bred with a C57BL/6 wild-type mouse are shown. The male offspring harbors either a 1-bp insertion mutation (1-bp ins) or a 14-bp deletion (14-bp del) mutation at the *Dmd* exon 23 site, generating a frameshift to be targeted by CjCas9. The PAM sequence of CjCas9 is shown in green and the target sequence in orange. Predicted CjCas9 cleavage sites are marked by red arrowheads. (D) Western blot analysis of extracts from TA muscles from wild-type (WT) and *Dmd* knockout mice (14-bp del and 1-bp ins) to detect dystrophin and GAPDH protein (control) is shown. (E) Histological analysis of TA muscles from wild-type and *Dmd* knockout mice (14-bp del and 1-bp ins) is shown. Dystrophin and laminin (control) are shown in red and green, respectively.

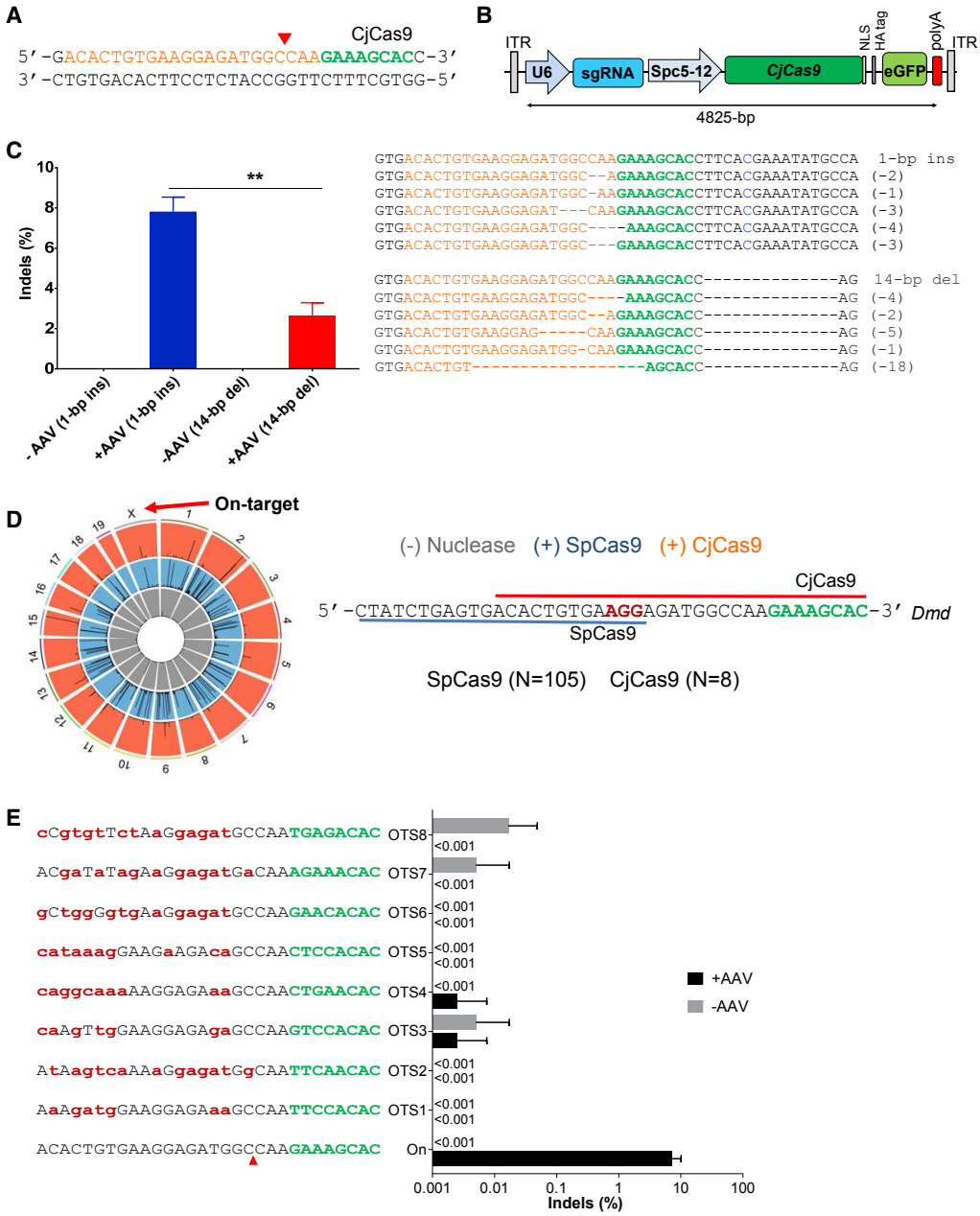

Figure 2. *In Vivo* Genome Editing with CjCas9 in TA Muscles of *Dmd* Knockout Mice

(A) CjCas9 target sequences in exon 23 of the murine *Dmd* gene. Predicted Cas9 cleavage sites are marked by red arrowheads. (B) Schematic diagram of the all-in-one AAV vector encoding the sgRNA and CjCas9 conjugated to EGFP is shown. (C) Indel frequencies (left) and representative mutant sequences (right) at the *Dmd* target site in TA muscles of *Dmd* knockout mice (1-bp ins and 14-bp del) 8 weeks after injection with AAV2/9-CjCas9 are shown. (Right) The inserted nucleotide in *Dmd* knockout mice harboring a 1-bp ins is shown in blue, the target sequence in orange, and the PAM sequence in green; the number of deleted bases is shown on the right. Error bars are shown as mean ± SEM (n = 3). One-way ANOVA and Tukey's post hoc tests, $^{**}p < 0.01$. (D) Digenome-seq analysis is shown. The Circos plot shows genome-wide DNA cleavage scores across the mouse genome. The red arrow indicates the on-target sites for CjCas9 (orange) or SpCas9 (blue). (Right) The target sites for SpCas9 and CjCas9 at the *Dmd* locus are indicated by the blue and orange lines, respectively. The numbers of *in vitro* cleavage off-target sites identified by Digenome-seq for the two enzymes are indicated. (E) Indel frequencies at Digenome-seq-captured off-target sites are shown. On, on-target site; OTS, off-target site. Mismatched nucleotides are shown in red and PAM sequences of CjCas9 in green. The red arrow indicates cleavage positions within the 22-bp target sequences. Error bars are shown as mean ± SEM (n = 3~4).

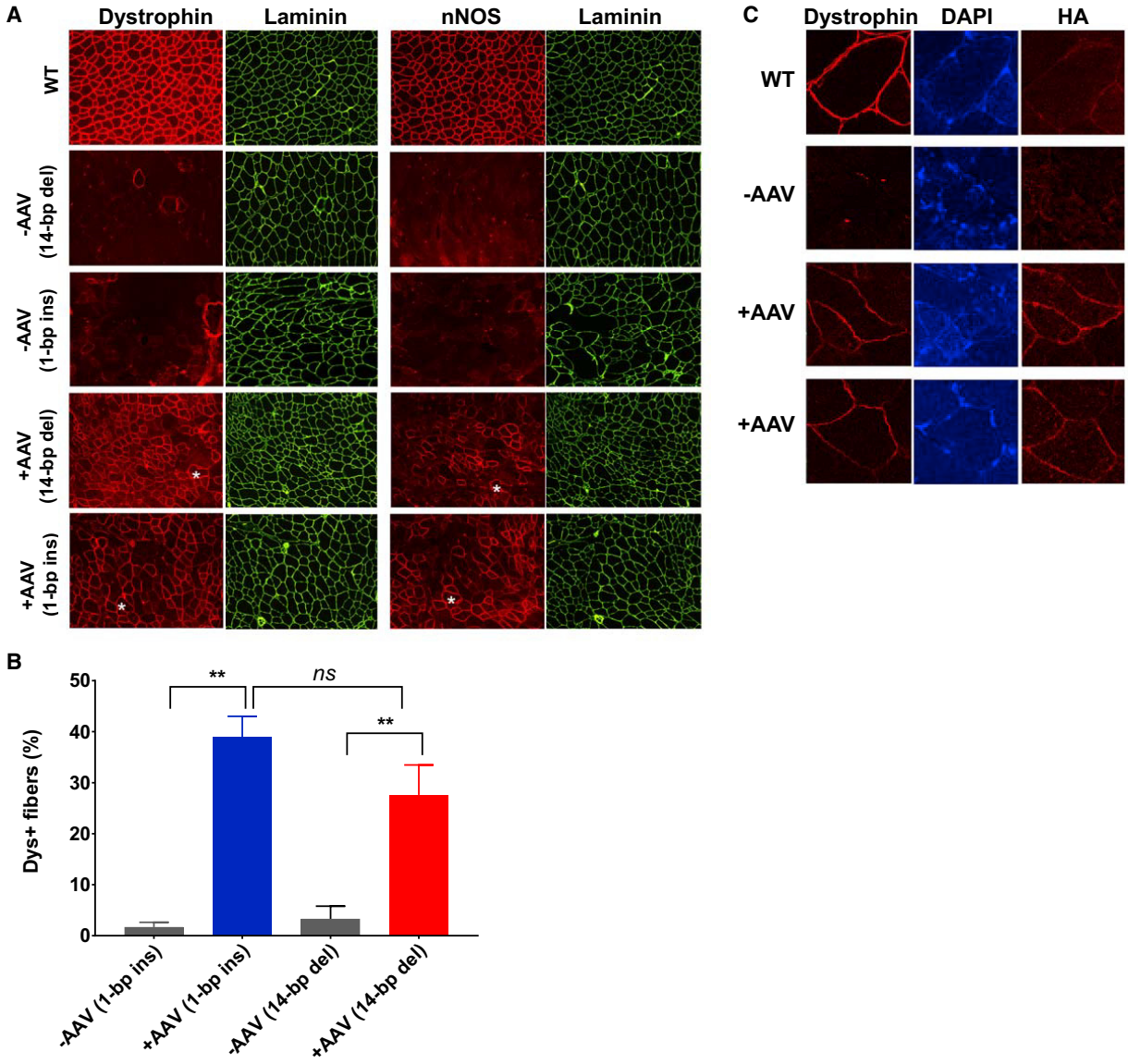

Figure 3. CjCas9-Mediated Dystrophin Correction Interacts with the Dystrophin-Associated Protein Complex

(A) Histological analysis of TA muscles from wild-type and *Dmd* knockout mice (1-bp ins and 14-bp del) 8 weeks after treatment with AAV2/9-CjCas9. The white stars indicate the same muscle fiber in dystrophin- and nNOS-stained sections. (B) Quantification of dystrophin-positive fibers in TA muscle cross sections is shown. Error bars are shown as mean ± SEM (n = 3). One-way ANOVA and Tukey's post hoc tests, **p < 0.01; ns, not significant. (C) Representative confocal images of dystrophin and HA-tag expression as a proxy for CjCas9 expression in TA muscle from mice treated with AAV2/9-CjCas9 are shown.

injected into TA muscles of 8-week-old male *Dmd* knockout mice harboring the 14-bp deletion mutation (1×10^{12} vgs/TA muscle) and *in situ* muscle physiology measurements were performed 7 weeks after injection. CjCas9 produced indels with a frequency of 2 ± 0.7% (Figure 4A), corresponding to an increase in protein expression as observed by western blot analysis (Figures 4B and S2). In the CjCas9-edited muscles, 26 ± 4% of the fibers were dystrophin positive (Figure 4*C*).

Despite the low frequency of indels, dystrophin expression induced by CjCas9 led to an increase in specific maximal force in AAV2/9-CjCas9-treated muscles compared to saline-injected contralateral TA muscles from *Dmd* knockout mice (Figure 4D). Furthermore, AAV2/9-CjCas9-treated muscles did not show any difference in the maximal specific force at 180 Hz compared to wild-type TA muscles from C57BL/6 mice (Figure 4D).

DISCUSSION

This study provides the evidence that AAV2/9-CjCas9 delivered to dystrophic muscles leads to restoration of the disrupted reading frame via the introduction of indels upstream of the PSC with

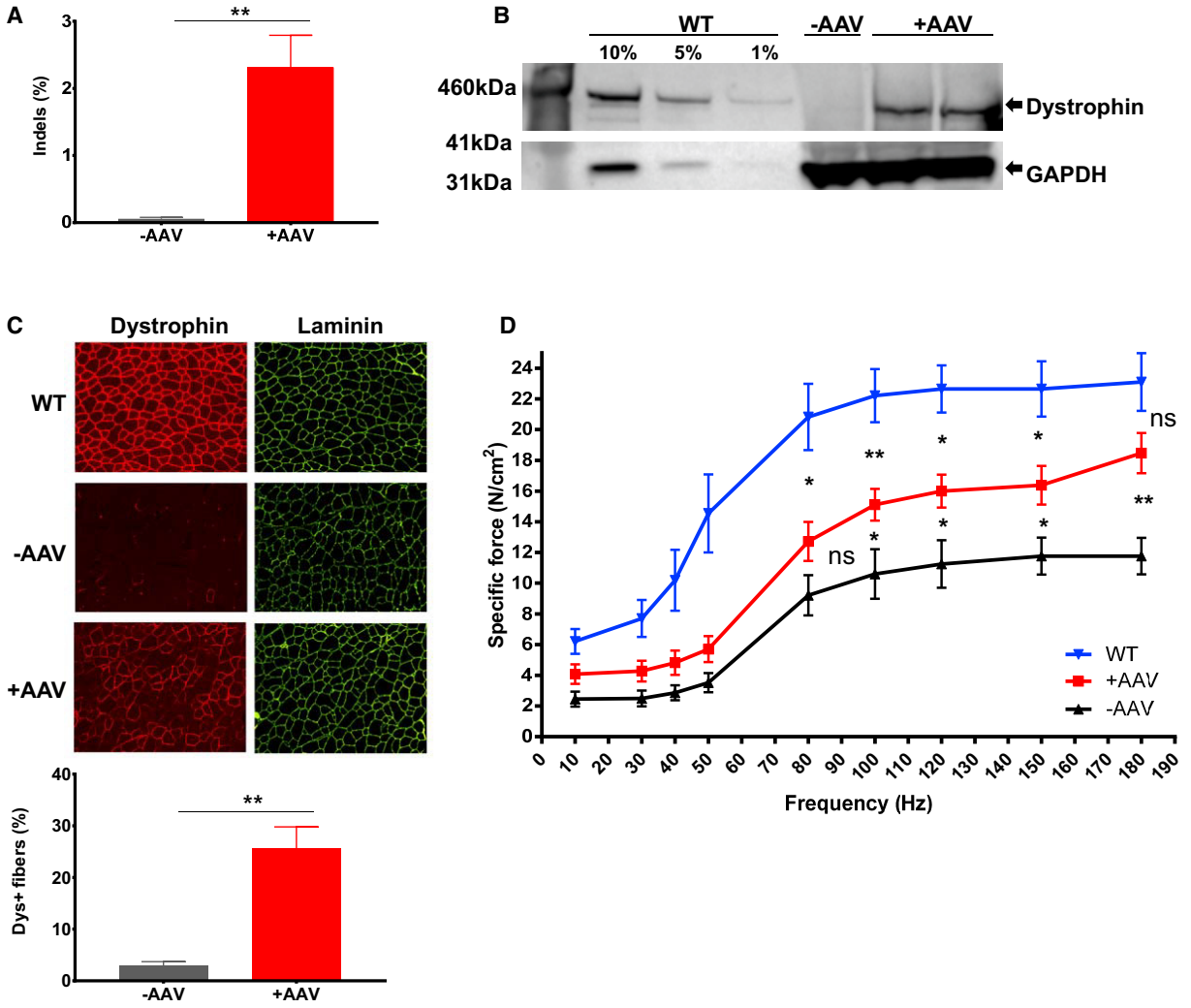

Figure 4. Gene Editing Increases Muscle Strength

(A) Indel frequencies at the *Dmd* target site in TA muscles from *Dmd* knockout mice (14-bp del) 7 weeks after intramuscular injection of AAV2/9-CjCas9. Error bars are shown as mean ± SEM (n = 5). (B) Western blot analysis of TA muscle samples from wild-type mice, *Dmd* knockout mice (14-bp del), and AAV2/9-CjCas9-treated *Dmd* knockout mice to detect dystrophin and GAPDH protein are shown. (C) (Top) Histological analysis of TA muscles from wild-type and *Dmd* knockout mice treated with AAV2/9-CjCas9 is shown. (Bottom) Quantification of dystrophin positive fibers in cross sections of TA muscle from *Dmd* knockout mice harboring the 14-bp deletion mutation is shown. Error bars are shown as mean ± SEM (n = 5). (D) The specific force (mN/cm^2) generated by the TA muscle is shown. Error bars are shown as mean ± SEM (n = 4). One-way ANOVA and Tukey's post hoc tests, *$p < 0.05$; **$p < 0.01$; ns, not significant.

high efficiency and specificity. We observed dystrophin-positive fibers interacting with neuronal nitric oxide synthase, supporting that the dystrophin protein functionally interacts with the dystrophin-associated protein complex in AAV2/9-CjCas9-injected muscles. In addition, muscle strength improvement was shown with indels induced at a frequency of 2% in the *Dmd* gene, suggesting that less than 2% reading frame correction is sufficient to induce a high level of dystrophin restoration that is correlated to an increase in dystrophic muscle strength.

The conventional exon deletion strategy used in previously reported CRISPR/Cas9-based studies for the treatment of DMD required dual guide RNAs to excise the exons;[18,21–24,26] an alternative strategy required a homology donor template to replace the nonsense mutation in the *mdx* mouse model.[19,21,36] In this study, we achieved NHEJ-mediated repair using CjCas9 and one sgRNA in the *Dmd* knockout mouse harboring a frameshift mutation. The use of one rather than two sgRNAs has great advantages in terms of increasing targeting efficiency and avoiding the possibility of homologous recombination between the two U6 promoter-sgRNA sequences during viral DNA packaging in cells.[37,38] Furthermore, a single AAV vector can be used to express Cas9 and its sgRNA, eliminating the need for two AAV vector systems.

In this study, targeted expression of CjCas9 and its sgRNA was achieved by the use of AAV serotype 9, which has tropism for skeletal and cardiac muscle[39] and, in the case of CjCas9, by the use of the SpC5-12 muscle-specific promoter. We linked the EGFP gene to the 3′ end of the CjCas9 gene with a T2A peptide sequence in between. This construct demonstrates the feasibility of adding other genetic elements in conjunction with CRISPR/Cas9 components to an all-in-one AAV vector. In addition, tracking of CjCas9-eGFP following systemic delivery into the whole mouse body should be applicable. Further development of CjCas9-mediated gene repair via HDR, in which missing exons in a donor template are inserted into *DMD*, may also contribute to the success of permanent gene correction with fully functional, wild-type dystrophin protein expression.

Taken together, our findings show that application of all-in-one AAV-CjCas9 system is highly efficient in correcting the disrupted reading frame and improves the dystrophic muscle strength. This study should accelerate translation of gene editing therapeutic approaches to the clinical stage and holds great potential for DMD. This strategy is also particularly appealing for use in other frameshift mutation-associated neuromuscular diseases that exhibit lifelong progression.

MATERIALS AND METHODS

Animals

The care, use, and treatment of all animals in this study were in strict agreement with the ARVO statement for the Use of Animals in College of Veterinary Medicine and the guidelines established by the Seoul National University Institutional Animal Care and Use Committee (SNU-150130-2). Eight-week-old male, specific-pathogen-free (SPF) *Dmd* knockout and C57BL6/J mice were used in this study. Mice were maintained under a 12 hr dark-light cycle.

Generation of *Dmd* Knockout Mice

Dmd knockout mice were generated by Macrogen (Seoul, Korea). To generate male *Dmd* mutants, a female pup (no. 14) heterozygous for a 1-bp insertion and a 14-bp deletion, both of which generated a PSC in *Dmd* exon 23, was cross-bred with a C57/BL6J wild-type male mouse. Mice were interbred and maintained in pathogen-free conditions at Macrogen. All animal experiments were performed in accordance with Korean Food and Drug Administration (KFDA) guidelines. Protocols were reviewed and approved by the Institutional Animal Care and Use Committees (IACUC) of Macrogen. All manipulations were conducted with the approval of the Institutional Animal Care and Use Committee. Briefly, C57BL/6N female mice were treated with pregnant mare serum gonadotropin (PMSG) and human chorionic gonadotropin (HCG). After 48 hr, these female mice were mated with C57BL/6N male mice. The next day, female mice containing vaginal plugs were sacrificed and fertilized embryos were harvested. A mixture of SpCas9 protein tagged with a nuclear localization signal and guide RNAs (gRNAs) targeting *Dmd* exon 23 was microinjected into one-cell embryos. Microinjected embryos were incubated at 37°C for 1 or 2 hr, after which they were transplanted into the oviducts of pseudopregnant recipient mice.

Construction of AAV Vector Plasmid Encoding CjCas9, Its sgRNA, and EGFP

A human codon-optimized CjCas9-coding sequence, derived from *Campylobacter jejuni* subsp. *Jejuni* NCTC 11168, was modified by PCR to include a nuclear localization signal (NLS) and an HA epitope, as well as self-cleaving T2A peptide and EGFP sequences at its 3′ end. The resulting sequence was cloned into the AAV inverted terminal repeat-based vector plasmid. The *trans*-activating CRISPR RNA (tracrRNA) sequence and the precursor CRISPR RNA (pre-crRNA) sequence were fused with a TGAA linker to form a sgRNA sequence.[28] *Dmd*-exon-23-targeting sgRNAs were transcribed under the control of the U6 promoter, and CjCas9 expression was controlled by the synthetic muscle-specific SPc5-12 promoter[40] in C2C12 myoblast cells and mouse TA muscles.

Cell Culture and Transfection of AAV Vector Plasmids

C2C12 (ATCC; CRL-1772) myoblast cells were maintained in DMEM (Welgene; cat. no. LM001-05) supplemented with 100 units per mL penicillin (Gibco; cat. no. 15140-122), 100 mg/mL streptomycin, and 10% fetal bovine serum (FBS) heat-inactivated (Welgene; cat. no. S 101-01). AAV vector plasmids expressing sgRNA and CjCas9 were transfected into cells with Lipofectamine 2000 (Invitrogen; cat. no. 11668019); cells were maintained in DMEM supplemented with 2% FBS for differentiation. After 5 days of transfection, genomic DNA was isolated using a DNeasy Blood & Tissue Kit (QIAGEN; cat. no. 69581).

Production and Titration of AAV Vectors

To produce AAV vectors, they were pseudotyped in AAV9 rep/cap capsids (pAAV2/9). HEK293T cells (ATCC; CRL-3216) were transfected with pAAV-ITR-CjCas9-sgRNA, pAAV2/9 encoding for AAV2rep and AAV9cap, and helper plasmid. HEK293T cells were cultured in DMEM with 2% FBS. Recombinant pseudotyped AAV vector stocks were generated using PEI coprecipitation with PEIpro (Polyplus-transfection) and triple transfection with plasmids at a molar ratio of 1:1:1 in HEK293T cells. After 72 hr of incubation, cells were lysed and particles were purified by iodixanol (Sigma-Aldrich) step-gradient ultracentrifugation. The number of vector genomes was determined by qPCR.

Intramuscular Injection of AAV

Intramuscular delivery of 5×10^{11} vgs to 1×10^{12} vgs of vector in physiological saline (40 μL) was performed via longitudinal injection into TA muscles of 8-week-old male Dmd-knockout mice anesthetized with 2%–4% isoflurane. Muscles were injected using an ultra-fine insulin syringe with a 31G needle (Becton Dickinson). As a negative control, C57BL/6J and *Dmd* knockout mice were injected with physiological saline only. We used 40 μL of AAV to deliver AAV to whole TA muscles. To confirm the injection target, the corresponding tendon reflexes were carefully checked.

Genomic DNA Extraction and Mutation Analysis

Muscle tissue was homogenized using tungsten carbide beads (3 mm; QIAGEN) and a TissueLyser II (QIAGEN). Genomic DNA was

isolated from the homogenized tissue using a NucleoSpin Tissue kit (Macherey-Nagel). On-target or off-target loci were amplified using 100 ng of genomic DNA for targeted deep sequencing. Deep sequencing libraries were generated by PCR with the following primers: *Dmd* exon 23, 5′-CTCATCAAATATGCGTGTTAGTGT-3′ (forward) and 5′- CACCAACTGGGAGGAAAGTT-3′ (reverse). TruSeq HT Dual index primers were used to label each sample. Pooled libraries were subjected to paired-end sequencing using MiniSeq (Illumina). Indel frequencies were calculated as described previously.[33]

Digenome Sequencing

Digenome-seq was performed as described previously.[33,34] Genomic DNA was isolated using a DNeasy Blood & Tissue Kit (QIAGEN) according to the manufacturer's instructions. Genomic DNA isolated from muscles of C57BL/6J mice (8 μg) was mixed with CjCas9 or SpCas9 protein (300 nM) and sgRNA (900 nM) in a 400 μL reaction volume (100 mM NaCl, 50 mM Tris-HCl, 10 mM $MgCl_2$, and 100 μg/mL BSA), and the mixture was incubated for 8 hr at 37°C. Digested genomic DNA was then incubated with RNase A (50 μg/mL) for 30 min at 37°C and purified again with a DNeasy Blood & Tissue Kit (QIAGEN). Digested DNA was fragmented using the Covaris system and ligated with adaptors for library formation. DNA libraries were subjected to whole-genome sequencing (WGS) using an Illumina HiSeq X Ten Sequencer at Macrogen. We used the Isaac aligner to generate a Bam file using the following parameters: ver. 01.14.03.12; mouse genome reference, mm10 from UCSC; base quality cutoff, 15; keep duplicate reads, yes; variable read length support, yes; realign gaps, no; and adaptor clipping, yes (adaptor: AGATCGGAAGAGC*; *GCTCTTCCGATCT).[41] A DNA cleavage score was assigned to each nucleotide position across the entire genome, using WGS data, according to the equation presented in Kim et al.[34] *In vitro* cleavage sites with DNA cleavage scores above the cutoff value of 2.5 were computationally identified.

Immunofluorescent Staining and Imaging of Tissue

TA muscles were excised from tendon to tendon, and OCT-embedded samples were rapidly frozen in liquid-nitrogen-cooled isopentane. To assess muscle pathology, 10-μm cryosections were prepared. Cross-section samples were immunostained with anti-dystrophin antibody (Abcam; 15277), anti-laminin antibody (Sigma; L0663), anti-HA tag antibody (Abcam; ab9110), and Alexa Fluor 594 (Invitrogen; A11037) or Alexa 488 antibodies (Invitrogen; A11006 and A11039). Muscle sections were imaged using a standard fluorescence (Nikon Eclipse Ti) microscope and a confocal microscope (LSM 710; Carl Zeiss). The scanning parameters were as follows: scaling (x = 0.208 μm/pixel; y = 0.208 μm/pixel); dimensions (x = 106.07 μm; y = 106.07 μm; channels: 4, 12-bit) with objective C-Apochromat 80×/1.20 W Korr M27. ZEN 2009 software was used to process the images. To track the expression of CjCas9, HA-tag-conjugated CjCas9 was visualized under confocal microscopy. Quantification of dystrophin-positive myofibers in muscle cross-sectional area was performed via counting the dystrophin expressing fibers in 844 to 1,182 individual myofibers per TA using Adobe Photoshop (n = 5 TAs per treatment group). The percentage of dystrophin-expressing fibers was calculated by dividing the number of dystrophin-positive fibers by the number of laminin-expressing fibers (a measure of the total number of fibers) and multiplying by 100. Sample randomization was done in this analysis.

Western Blotting

Muscles were homogenized in 300 μL of homogenization buffer (Thermo Fisher; 89900). Protein extracted from the C57BL/6 muscles were loaded at 10%, 5%, and 1% of total protein (30 μg), whereas 30 μg of protein was loaded in the AAV-treated and mock control group. Thus, the band for GAPDH represents the corresponding protein loading of the samples. Proteins were separated on a 3%–8% polyacrylamide Tris-acetate gel (Invitrogen, EA0375) and transferred onto a 0.2 μm nitrocellulose membrane (Hybond ECL membrane; Amersham Biosciences, 10600004). Dystrophin was detected using rabbit anti-dystrophin antibodies (Abcam; ab15277); GAPDH was detected with anti-GAPDH antibodies (Abcam; ab9485) as an internal control. The membrane was incubated with primary antibodies at room temperature for 1 hr. Goat anti-rabbit immunoglobulin G (IgG)-horseradish peroxidase (HRP) antibody (Abcam; ab6721) was used for signal detection. The membrane was exposed to SuperSignal West Pico Chemiluminescent Substrate (Thermo Scientific, NC14080KR), and Ez-Capture MG (ATTO, AE-9300Ez) was used for digital imaging. The experiments were repeated three times, and representative results performed in duplicate are shown in this study.

In Vivo Force Measurements

Seven weeks after AAV2/9-CjCas9 injection, the function of both TA muscles from each mouse was assessed. This procedure was adapted from standard protocols[42,43] and has been previously described.[44] Mice were deeply anesthetized and were carefully monitored throughout the experiment to ensure that there was no reflex response to toe pinch. The distal tendon of the TA muscle was dissected from surrounding tissue and tied with 4.0 braided surgical silk (Interfocus, Cambridge, UK). The sciatic nerve was exposed and superfluous branches axotomized, leaving the TA motor innervation via the common peroneal nerve intact. The foot was secured to a platform and the ankle and knee immobilized using stainless steel pins. The TA tendon was attached to the lever arm of a 305B dual-mode servomotor transducer (Aurora Scientific, Aurora, ON, Canada) via a custom-made steel s-hook. TA muscle contractions were elicited by stimulating the distal part of common peroneal nerve via bipolar platinum electrodes, using supramaximal square-wave pulses of 0.02 ms (701A stimulator; Aurora Scientific). Data were acquired and the servomotors controlled using a Lab-View-based DMC program (Dynamic Muscle Control and Data Acquisition; Aurora Scientific). Optimal muscle length (Lo) was determined by incrementally stretching the muscle using micromanipulators until the maximum isometric twitch force was achieved. Maximum isometric tetanic force (Po) was determined from the plateau of the force-frequency relationship following a series of stimulations at 10, 30, 40, 50, 80, 100, 120, 150, and 180 Hz. A 1-min rest period was allowed between each tetanic contraction. The specific force (N/cm^2) was

calculated by dividing Po by the TA muscle cross-sectional area. The overall cross-sectional area was estimated using the following formula: muscle weight (g)/(TA fiber length [Lf; cm] × 1.06 [g/cm^3]).

Statistical Analysis

No statistical methods were used to predetermine sample size for *in vitro* or *in vivo* experiments. To avoid scientific bias, we randomized the mice from different litters for the *in vivo* experiments before injections. Furthermore, scientists were blinded to the samples during analysis of dystrophin quantification and during muscle strength assessment by electrophysiology. All group results are expressed as mean ± SEM. Comparisons between groups were made using the one-way ANOVA with Tukey's post hoc tests. Statistical significance as compared to untreated controls is denoted with *$p < 0.05$, **$p < 0.01$, and ns for not significant in the figures and figure legends. Statistical analysis was performed in Graph Pad PRISM 5.

ACCESSION NUMBER

The deep sequencing data from this study have been submitted to the NCBI Sequence Read Archive (http://www.ncbi.nlm.nih.gov/sra): SRP131242.

SUPPLEMENTAL INFORMATION

Supplemental Information includes two figures and one table and can be found with this article online at https://doi.org/10.1016/j.ymthe.2018.03.018.

AUTHOR CONTRIBUTIONS

T.K., L.P., G.D., and J.-S.K. designed the research. T.K., N.B.L-N., E.K., A.M., D.K., O.C., and H.-Y.C. performed the experiments. T.K., L.P., and A.M. wrote the manuscript, and G.D. and J.-S.K. critically edited it with comments. All authors read and approved the final manuscript.

CONFLICTS OF INTEREST

J.-S.K. is a co-founder and shareholder of ToolGen, and E.K. has filed patent applications. The remaining authors declare no competing financial interests.

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