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*Research Article*  
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Hyperkalemic periodic paralysis (HyperKPP) produces myotonia and attacks of muscle weakness triggered by rest after exercise or by K⁺ ingestion. We introduced a missense substitution corresponding to a human familial HyperKPP mutation (Met1592Val) into the mouse gene encoding the skeletal muscle voltage-gated Na⁺ channel Nav1.4. Mice heterozygous for this mutation exhibited prominent myotonia at rest and muscle fiber-type switching to a more oxidative phenotype compared with controls. Isolated mutant extensor digitorum longus muscles were abnormally sensitive to the Na⁺/K⁺ pump inhibitor ouabain and exhibited age-dependent changes, including delayed relaxation and altered generation of tetanic force. Moreover, rapid and sustained weakness of isolated mutant muscles was induced when the extracellular K⁺ concentration was increased from 4 mM to 10 mM, a level observed in the muscle interstitium of humans during exercise. Mutant muscle recovered from stimulation-induced fatigue more slowly than did control muscle, and the extent of recovery was decreased in the presence of high extracellular K⁺ levels. These findings demonstrate that expression of the Met1592Val Na⁺ channel in mouse muscle is sufficient to produce important features of HyperKPP, including myotonia, K⁺-sensitive paralysis, and susceptibility to delayed weakness during recovery from fatigue.

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Targeted mutation of mouse skeletal muscle sodium channel produces myotonia and potassium-sensitive weakness

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Hyperkalemic periodic paralysis (HyperKPP) produces myotonia and attacks of muscle weakness triggered by rest after exercise or by K+ ingestion. We introduced a missense substitution corresponding to a human familial HyperKPP mutation (Met1592Val) into the mouse gene encoding the skeletal muscle voltage-gated Na+ channel Na\textsubscript{v}1.4. Mice heterozygous for this mutation exhibited prominent myotonia at rest and muscle fiber type switching to a more oxidative phenotype compared with controls. Isolated mutant extensor digitorum longus muscles were abnormally sensitive to the Na+/K+ pump inhibitor ouabain and exhibited age-dependent changes, including delayed relaxation and altered generation of tetanic force. Moreover, rapid and sustained weakness of isolated mutant muscles was induced when the extracellular K+ concentration was increased from 4 mM to 10 mM, a level observed in the muscle interstitium of humans during exercise. Mutant muscle recovered from stimulation-induced fatigue more slowly than did control muscle, and the extent of recovery was decreased in the presence of high extracellular K+ levels. These findings demonstrate that expression of the Met1592Val Na+ channel in mouse muscle is sufficient to produce important features of HyperKPP, including myotonia, K+-sensitive paralysis, and susceptibility to delayed weakness during recovery from fatigue.

Introduction
Hyperkalemic periodic paralysis (HyperKPP) is one of several familial disorders of muscle excitability caused by missense mutations in the skeletal muscle Na+ channel Na\textsubscript{v}1.4 (1, 2). Na\textsubscript{v}1.4 normally allows rapid propagation of the muscle action potential along the surface membrane and radially into the myofiber via the transverse (t) tubules, where depolarization triggers Ca\textsuperscript{2+} release from the sarcoplasmic reticulum. Sarcolemmal excitability is transiently impaired during an attack of periodic paralysis (3). HyperKPP was originally distinguished from other forms of periodic paralysis by the absence of hypokalemia (4) and the observation of increasing firing of muscle action potentials (myotonia) that produces muscle stiffness (6). Weakness can be provoked by immobility after strenuous exercise, ingestion of K+ salts, fasting, cold exposure, emotional stress, or glucocorticoids (1, 7–10), although the triggers can be highly variable even among members of a single affected family. Attacks can be prevented by carbohydrate ingestion, mild exercise, thiazide diuretics, or carbonic anhydrase inhibitors (1, 11). The latter agents, and inhaled β-adrenergic agonists (9, 12) or intravenous calcium gluconate (5, 6), may also ameliorate symptoms during an attack. Despite treatment, however, individuals with HyperKPP frequently develop a slowly progressive vacuolar myopathy that affects proximal muscles by the third decade (10, 13, 14).

The detection of an aberrantly increased inward Na+ current in muscle from HyperKPP patients (15, 16) preceded the linkage of HyperKPP to a locus near the SCN4A gene encoding Na\textsubscript{v}1.4 (17). Subsequent studies identified more than 30 missense mutations in SCN4A among individuals with overlapping phenotypes of HyperKPP and related disorders (1, 2, 18). N\textsubscript{a\textsubscript{v}}1.4 comprises a pore-forming 260-kDa protein, the α-subunit (Figure 1A), which associates with a 38-kDa β\textsubscript{1} subunit (19). The two most common mutations identified in HyperKPP include Thr704Met and Met1592Val, which have each been observed in approximately 30% of kindreds (10). Both of these substitutions are located in regions near the cytoplasmic face of the channel α-subunit. Because distinct Na+ channel isoforms are present in skeletal muscle, cardiac muscle, brain, and peripheral nerve, mutations that alter the properties of N\textsubscript{a\textsubscript{v}}1.4 α-subunits are not expected to affect Na+ channel function in tissues other than skeletal muscle.

Electrophysiological studies of mutant Na+ channels in heterologous expression systems have demonstrated functional abnormalities that may contribute to the phenotypic heterogeneity observed among different families with HyperKPP and related myotonic disorders (1, 2). For instance, HyperKPP mutant Na+ channels can exhibit enhanced activation, impaired slow inactivation, and a persistent noninactivating inward current (20–22). In contrast, other Na+ channel mutants that cause myotonic phenotypes without weakness typically show impaired fast inactivation but do not maintain a persistent Na+ current (2). A 2-compartment model of the muscle surface membrane and t tubule system suggested that the exaggerated excitability in HyperKPP depends on both...
The proportion of noninactivating Na+ channels and the degree of activity-driven K+ accumulation within t tubules (21, 23, 24). Consistent with this, electrophysiological analyses of muscle bundles from individuals with HyperKPP show that paralysis is caused by aberrant depolarization of the muscle membrane (3, 15, 16, 25), but a link to the clinical triggers is incompletely understood.

The aim of the present study was to determine whether introduction of a mutation corresponding to the human Met1592Val substitution into the mouse NaV1.4 gene produces features similar to HyperKPP in mice and provides new insights regarding the disease mechanisms. While all individuals with HyperKPP share a K+-sensitive phenotype (1, 26), considerable variability exists with respect to the triggers and severity of attacks in vivo (10, 14). Furthermore, inductive attacks of human HyperKPP occur with quite unpredictable success, and the relationship of factors such as muscle cooling to symptoms is not well defined. For example, exercise and cold are reported as triggers of weakness by patients with the Met1592Val mutation, but only with probabilities of 0.73 and 0.38, respectively (10). While improved electrodiagnostic tests show promise in discriminating among different subgroups of muscle channelopathies (27, 28), an in vitro muscle preparation could allow further dissection of the complex physiological interactions that contribute to episodic paralysis. Given the clinical variability among individuals with HyperKPP, the first objective was therefore to determine whether the mutant mice exhibit 4 physiological hallmarks of the disease, including (a) myotonic activity in vivo; (b) reduced muscle force development at elevated extracellular [K+] (3) in vitro mimicking episodic paralysis; (c) amelioration of weakness with increased [Ca2+] in vitro; and (d) development of nonepisodic muscle weakness with aging.
In response to changes in functional demands, skeletal muscle fibers can modulate their metabolic capacity, contractile protein expression, and susceptibility to fatigue (29–31). Increased muscle activity produces adaptive changes via calcineurin-dependent signaling (32) and transcriptional regulators such as PPARγ coactivator-1α (PGC-1α) (33). PGC-1α not only increases expression of slow-twitch muscle contractile protein isoforms by coactivating nuclear respiratory factor 1 (Nrf1) (33). The second objective was therefore to examine whether the presence of both the silent H<sub>pai</sub> allele and the actual HyperKPP mutation (causing loss of an N<sub>pai</sub> site) were verified during breeding using PCR amplification of genomic DNA followed by restriction digestion (Figure 1D). When heterozygous mutant (+/m) mice were bred with each other, we observed the following genotype frequencies at 30 days of age (n = 146 offspring): normal (+/+), 35.6% (n = 52); heterozygous mutant (+/m), 63.0% (n = 92); and homozygous mutant (m/m), 1.4% (n = 2). These results indicated that (a) the (m/m) genotype was underrepresented at 30 days (P < 0.001 using χ<sup>2</sup> analysis), and (b) there was no selection bias against the heterozygous (+/m) genotype by 30 days (P = 0.54 for selection). Occasionally, we also observed dead pups within a day after birth; we genotyped one such litter and found that all 4 dead pups exhibited the (m/m) genotype (Figure 1D; lane P is representative), suggesting that selection against (m/m) may occur by the first postnatal day (P < 0.05). Overall, these observations imply that the absence of a normal mNa<sub>1.4</sub> allele in (m/m) homozygous mutants.

**Results**

**Targeted substitution of HyperKPP variant Met1592Val into mouse Na<sub>1.4</sub>.** We introduced a mutation corresponding to human Met1592Val (Figure 1A) into the gene encoding mouse Na<sub>1.4</sub> (mNa<sub>1.4</sub>) by homologous recombination to produce the line B6.129S4-Scn4a<sup>tm1Ljh</sup> (see Supplemental Methods; supplemental material available online with this article; doi:10.1172/JCI32638DS1). A 630-bp unique 3′-UTR probe identified 3 BAC clones derived from a mouse 129/Sv ES cell library that contained mNa<sub>1.4</sub> genomic sequence. Restriction mapping and sequence analysis of the region encompassing exons 17–24 revealed exon/intron boundaries identical to that of the human Na<sub>1.4</sub> gene (34).

A 12.1-kb targeting sequence for homologous recombination introduced the disease mutation and an adjacent silent H<sub>pai</sub> site into exon 24 (Figure 1A). The phosphoglycerate kinase–promoted neomycin phosphotransferase gene (PGKneo) was inserted in reverse orientation to that of the human Na<sub>1.4</sub> gene (34). The presence of both the silent H<sub>pai</sub> marker and the actual HyperKPP mutation (causing loss of an N<sub>pai</sub> site) were verified during breeding using PCR amplification of genomic DNA followed by restriction digestion (Figure 1D). When heterozygous mutant (+/m) mice were bred with each other, we observed the following genotype frequencies at 30 days of age (n = 146 offspring): normal (+/+), 35.6% (n = 52); heterozygous mutant (+/m), 63.0% (n = 92); and homozygous mutant (m/m), 1.4% (n = 2). These results indicated that (a) the (m/m) genotype was underrepresented at 30 days (P < 0.001 using χ<sup>2</sup> analysis), and (b) there was no selection bias against the heterozygous (+/m) genotype by 30 days (P = 0.54 for selection). Occasionally, we also observed dead pups within a day after birth; we genotyped one such litter and found that all 4 dead pups exhibited the (m/m) genotype (Figure 1D; lane P is representative), suggesting that selection against (m/m) may occur by the first postnatal day (P < 0.05). Overall, these observations imply that the absence of a normal mNa<sub>1.4</sub> allele in (m/m) homozygous mutants.

**Figure 2**

Mutant Na<sup>+</sup> channel mRNA and protein are expressed in mouse skeletal muscle tissue. (A) Northern blots of total RNA extracted from pooled hind-limb skeletal muscle, quadriceps, gastrocnemius/soleus, heart, or brain tissues (5 μg loaded per lane; n = 3–8 mice per group). The 3′-UTR probe specific for mNa<sub>1.4</sub> hybridized to an 8.5-kb full-length Na<sup>+</sup> channel mRNA in both normal (+/+) and mutant (+/m) muscle samples but not those from heart or brain (top panel). The blot was rehybridized with a GAPDH probe (bottom panel). (B) RT-PCR of total RNA from (+/+) or (+/m) mouse muscle using primers c (exon 23) and b (exon 24). Digestion of the mutant RT-PCR product with H<sub>pai</sub> (producing 0.89-kb and 0.54-kb fragments) or N<sub>pai</sub> (preserving a 0.71-kb fragment) demonstrated that approximately 30%–50% of transcripts in mutant muscle encoded the Meta1592Val variant. The lane labeled “M” shows a 100-bp marker DNA ladder. (C) Western blot of membrane proteins isolated from (+/+), (+/m), or (m/m) mouse quadriceps muscle, heart (HT), and brain (BN) tissues (10 μg loaded per lane). The L/D3 monoclonal antibody specifically recognizes Na<sub>1.4</sub> but not cardiac or brain Na<sup>+</sup> channel isoforms.

Mutant Na⁺ channel mRNA and protein expression in skeletal muscle. Total RNA was isolated from hind-limb muscles, heart, and brain from (+/+) or (+/m) mice, and Northern blot analysis using a hybridization probe specific for Na1.4 transcripts identified an 8.5-kb mRNA in skeletal muscle that was absent from heart and brain tissues (Figure 2A). Digestion of an RT-PCR product with HpaI or NsiI identified expression of mutant Na1.4 mRNA in all (+/m) muscles examined (Figure 2B). The Met1592Val mutant sequence constituted 42% ± 11% of the total Na1.4 RT-PCR products from each heterozygous muscle as quantified by optical density of the digested PCR product.

The expression of mNa1.4 protein was determined by Western blot analysis using the L/D3 antibody, which specifically recognizes the skeletal muscle Na⁺ channel isoform (19). A 260-kDa species, consistent with mNa1.4, was observed in each quadriceps sample but not in membrane proteins from heart or brain (Figure 2C). Total mNa1.4 protein expression as determined by Western blot appeared slightly decreased, by 1.4 ± 0.4-fold, in mutant (+/m) compared with normal (+/+) muscle membranes, but this difference did not reach statistical significance (P = 0.07). Although mNa1.4 appeared decreased by approximately 3-fold in (m/m) compared with normal (+/+) muscle, perhaps reflecting down-regulation of poorly inactivating Na⁺ channels in the absence of the normal allele, the small sample size for (m/m) did not allow statistical validation of this difference.

Myotonia in (+/m) mutant muscle and accelerated myopathic abnormalities in (m/m) muscle. Heterozygous (+/m) mice had normal locomotor activity without any observed spontaneous episodes of weakness. However (+/m) mice exhibited increased muscle irritability during electromyography in response to needle movement and robust myotonia in hind-limb muscles from at least 1 month of age, while control (+/+) siblings had normal excitability and no electrical myotonia (Figure 3, A and B, and Supplemental Videos 1 and 2). Histological examination of muscle from (+/m) mice at 4 months of age suggested only mild myopathic changes compared with that from normal siblings (Figure 3, C and D), with scattered internalized nuclei suggesting regeneration of damaged muscle fibers by satellite cells. Compared with their (+/m) siblings, the surviving homozygous (m/m) mice showed (a) obvious fixed limb weakness with muscle atrophy and (b) unusual hind-limb clasping behavior when lifted by the tail (examples shown in Figure 3G and Supplemental Video 3). At 2.8 months of age (m/m) muscle revealed prominently increased fiber size variation, frequent internalized nuclei, and large scattered vacuoles at various stages of evolution (E). Normal extension of hind limbs observed for a (+/m) mouse at 2.8 months of age upon being held by the tail. (G) Abnormal clasping response exhibited by a (m/m) sibling at 2.8 months. This (m/m) mouse also had prominent hind-limb weakness and decreased locomotor activity compared with its (+/m) sibling (see Supplemental Video 4).
myosin immunostaining (35) revealed a large increase in type IIA fibers in the mutant tibialis anterior muscle compared with control (Figure 4, E and F). A similar shift toward a more oxidative muscle phenotype was observed for quadriceps and gastrocnemius muscles (+/m) compared with (+/+) muscles (data not shown).

The contents of PGC-1α and the glycolytic enzyme GAPDH in muscle lysates were detected by Western blotting, with equal amounts of total protein loaded per lane (Figure 4G). We observed an increase of PGC-1α by 2.1 ± 0.5-fold (P < 0.05) in mutant compared with normal tibialis anterior muscle at 1 year of age. This increased level did not differ significantly from the normal level of PGC-1α in soleus (P = 0.53), a slow-twitch oxidative muscle. The higher glycolytic capacity of normal tibialis anterior compared with soleus muscle was reflected by a 2.4 ± 0.6-fold higher GAPDH content (P < 0.01) on the same blot. We observed that mutant tibialis anterior muscle at 1 year of age expressed only slightly lower GAPDH compared with control (86% ± 8% of control, P = 0.05), suggesting that the mutant muscle retained a high glycolytic capacity. The signal ratio of PGC-1α to GAPDH should be independent of loading variation and provides a relative oxidative index, with largest values expected for slow oxidative muscle (type I), intermediate values for fast oxidative-glycolytic muscle (type IIA), and lowest values for fast glycolytic muscle (type IIB). This ratio increased by 2.4 ± 0.5-fold for mutant compared with control tibialis anterior muscles (P < 0.05). The maintenance of a high GAPDH level and the increase in PGC-1α are consistent with our independent observations of a shift toward type IIA immunostaining (Figure 4, E and F) and a more fatigue-resistant phenotype (see below) for mutant muscles that contain fast fibers. Furthermore, these results suggest that PGC-1α may be involved in specifying properties of type IIA in addition to type I myofibers (33).

Reduced contractile force and slowed relaxation in mutant (+/m) muscle. To evaluate muscle contractile properties under defined physiological conditions, we isolated extensor digitorum longus (EDL) muscle from 8- to 14-month-old mice and recorded the twitch force produced by direct stimulation with 1-ms current pulses in an organ bath at 25°C (Figure 5A). Under baseline ionic conditions of 4 mM [K⁺]o and 2 mM [Ca²+]o, a single supramaximal current pulse elicited twitch force from mutant EDL muscle that was only 44% of that generated by age-matched control muscle (Figure 5A, P < 0.01). Furthermore, although the rapidity of contraction was similar for both groups, the time to half-relaxation (twitch T<sub>1/2R</sub>) was prolonged by 110% (P < 0.01) and 54% (P < 0.01), respectively, for mutant compared with control EDL muscle (Figure 5B). Muscle relaxation from the last stimulus applied during a 50- or 100-Hz pulse train (tetanic T<sub>1/2R</sub>) was also prolonged, by 39% (P < 0.01) and 30% (P < 0.01), respectively, for mutant compared with control EDL muscle. The delayed relaxation likely contributed to the greater degree of force buildup (peak tetanic force/single-twitch force ratio) observed for mutant compared with control muscle during 50- and 100-Hz stimulation (Figure 5B, P < 0.01). Mutant EDL muscle also had 34% less tetanic force (P < 0.05) elicited during 100-Hz stimulation when compared with control EDL muscle. The group of younger mice (ages 3–5 months) showed prolongation of the tetanic rising phase (τ) by only 39% (P < 0.01) and 30% (P < 0.04) and the tetanic T<sub>1/2R</sub> by only 26% (P < 0.01) and 22% (P < 0.01) during 50- and 100-Hz stimulation, respectively (data not shown). Overall...
all, these results indicated that expression of mutant Na\(_+\)1.4 channels in EDL muscle can alter the magnitude and rate of tetanic force generation in an age-dependent manner.

**Sustained weakness of mutant EDL muscle upon exposure to 10 mM \([K^+]_o\)**. We next examined the consequences of altered extracellular K\(^+\) and Ca\(^{2+}\) upon peak contractile force for normal (+/++) and mutant (+/+) muscles. As shown in Figure 6, isolated EDL muscles were equilibrated in a starting bath solution containing 4 mM \([K^+]_o\), and 1.3 mM \([Ca^{2+}]_o\), and the peak tetanic force obtained every 3 minutes was normalized to the force produced at the start of the stimulation protocol. We initially tested whether EDL muscles expressing the mutant Na\(^+\) channel showed any unexpected sensitivity to low \([K^+]_o\) (Figure 6A). Upon reduction of \([K^+]_o\), from 4 mM to 1.2 mM, the mutant muscle exhibited a mild decrease in tetanic force that did not differ from control \((P = 0.15)\). The test condition was followed by exposure to a recovery solution containing normal \([K^+]_o\) (4 mM) and elevated \([Ca^{2+}]_o\) (4 mM) to assess for reversibility of any observed changes. The rationale for the elevated \([Ca^{2+}]_o\) is that Ca\(^{2+}\) can help to repolarize the muscle cell membrane (36, 37) should any of the test conditions cause depolarization-induced weakness. As shown in Figure 6A, the mutant muscle regained force more rapidly than control in the recovery solution \((P < 0.01)\).

For the experiments in Figure 6, A–D, and Figure 7, B and C, the recovery from each test occurred in 4 mM \([K^+]_o\) and 4 mM \([Ca^{2+}]_o\).

We next evaluated the effects of mildly raising \([K^+]_o\), from 4 mM to 8 mM upon EDL contraction. As shown in Figure 6B, upon raising external \([K^+]_o\), the peak tetanic force for mutant EDL transiently decreased by 46% within 5 minutes \((P < 0.001)\), while control EDL increased by 3%. The mutant EDL recovered back to the baseline force within 15 minutes despite continued exposure to 8 mM \([K^+]_o\), indicating that this level of \([K^+]_o\) was insufficient to produce sustained weakness. During moderate exercise in humans, the muscle interstitial \([K^+]_o\) normally reaches 8–10 mM, being 4–6 mM higher than venous \([K^+]_o\) (38). So, although individuals with HyperKPP typically experience severe weakness associated with venous \([K^+]_o\) levels acutely rising to only 4.5–6.5 mM, the increase is expected to be greater in the muscle interstitium and most likely within the t-tubules.

We thus hypothesized that 10 mM \([K^+]_o\) would more closely mimic the interstitial \([K^+]_o\) level achieved during an attack of HyperKPP triggered after exercise. Figure 6C shows that within 7 minutes after raising \([K^+]_o\) to 10 mM, we observed a dramatic loss of force by 88% for mutant compared with only 9% for control \((P < 0.001)\), and the mutant partially recovered within 15 minutes. Furthermore, while exposure of EDL to 10 mM \([K^+]_o\) for 28 minutes caused a mild monophasic decline in force by 22% for control, the mutant muscle exhibited an additional late phase of force decline to less than 30% of the starting value \((P < 0.001)\). The weakness was reversible, since the mutant muscle quickly regained full force upon exposure to the recovery solution.

Prolonged muscle activity can result in a depletion of t-tubular Ca\(^{2+}\) (39), so the myotonic activity of mutant muscle may also be expected to lower the t-tubular \([Ca^{2+}]_o\). Furthermore, in contrast to elevated \([Ca^{2+}]_o\), lowered \([Ca^{2+}]_o\) can worsen tetanic weakness of normal mouse EDL muscle subjected to impaired K\(^+\) and Na\(^+\) gradients by contributing to action potential failure (37). Indeed,
a preliminary experiment demonstrated that lowering [Ca\(^{2+}\)]\(_o\) to 0.5 mM caused a significant decrease in mutant muscle force by itself and also intensified the effect of 8 mM [K\(^+\)]\(_o\), as shown in Supplemental Figure 1. In Figure 6D, we observed that lowering [Ca\(^{2+}\)]\(_o\) to 0.5 mM also exacerbated the weakness produced by raising [K\(^+\)]\(_o\) to 10 mM without affecting the time course of the triphasic response or the reversibility upon exposure to recovery solution. Overall, these results indicated that isolated mutant EDL exhibits an aberrant [K\(^+\)]-induced weakness that can be modulated by ambient [Ca\(^{2+}\)] levels.

**Increased sensitivity of mutant EDL to inhibition of the Na\(^+\)/K\(^+\) pump.** Two-electrode voltage clamp studies of isolated flexor digitorum brevis fibers revealed a 30% increase (P < 0.02) in the persistent Na\(^+\) current for heterozygous (+/+m) fibers (data not shown). Because the high-capacity Na\(^+\)/K\(^+\)-ATPase pump in muscle contributes strongly toward maintaining the Na\(^+\) and K\(^+\) gradients required for normal muscle membrane excitability, we hypothesized that an abnormally increased Na\(^+\) influx might render mutant muscle more vulnerable than control to partial inhibition of Na\(^+\)/K\(^+\) pump activity. In Figure 7A, the tetanic force elicited from EDL muscle in 4 mM [K\(^+\)]\(_o\) and 1.3 mM [Ca\(^{2+}\)]\(_o\), decreased by 31% for mutant compared with only 4% for control (P < 0.001) after exposure to 0.5 μM ouabain for 15 minutes. Contraction of mutant EDL was nearly abolished after subsequent exposure to 2.0 μM ouabain for 15 minutes, while control muscle force declined much more slowly (P < 0.001). Partial recovery of muscle force upon washout of ouabain occurred over 20 minutes for mutant EDL (Figure 7A) and for control (data not shown).

To test whether Na\(^+\)/K\(^+\) pump activity may have contributed to the force recovery observed during exposure to high [K\(^+\)]\(_o\), in Figure 6, B and C, we exposed EDL muscles to 0.5 μM ouabain during challenge with 8 mM [K\(^+\)]\(_o\) (Figure 7B) or 10 mM [K\(^+\)]\(_o\) (Figure 7C). Under these conditions, ouabain exacerbated the effects of high [K\(^+\)]\(_o\) to reduce tetanic force. In 8 mM [K\(^+\)]\(_o\), the mutant EDL force declined within 7 minutes by 73% with ouabain present (Figure 7B) compared with only a 46% decline with ouabain absent (Figure 6B, P < 0.01). We also observed a partial and transient recovery of force after 7 minutes (Figure 7B), as would be expected if increased intracellular Na\(^+\) stimulated the total Na\(^+\)/K\(^+\) pump activity considerably above its basal level, despite partial inhibition of the pumps by ouabain. After 15 minutes, though, in contrast to the full recovery during 8 mM [K\(^+\)]\(_o\) that occurred in the absence of
ouabain (Figure 6B), we observed an ongoing loss of force in the presence of ouabain (Figure 7B). This suggests that a high $\text{Na}^+$/K$^+$ pump capacity may be required to prevent sustained weakness of mutant muscle during challenge with 8 mM [K$^+$].

Upon exposure to 10 mM [K$^+$], we observed a dramatic initial decline in force for mutant EDL within 7 minutes whether ouabain was present or not (Figure 6C and Figure 7C). However, the partial rebound of tetanic force after 7 minutes (Figure 6C) was prevented in the presence of ouabain (Figure 7C, $P < 0.05$). Overall, these findings suggest that a high $\text{Na}^+$/K$^+$ pump capacity can significantly protect the mutant muscle from the consequences of extracellular K$^+$ challenge, probably by helping to maintain ionic homeostasis of Na$^+$ and K$^+$ and by its electrogenic effect to hyperpolarize the membrane. We also observed a more rapid restoration of force for mutant compared with control muscle during exposure to the recovery buffer (Figure 7, B and C), similar to that observed during the recovery in Figure 6.

### Figure 7

Mutant (+/m) EDL was more sensitive than control (+/+)) to inhibition of force by ouabain (OB), which also exacerbated the weakness produced by elevated [K$^+$]. Isolated EDL muscles from 8.9 ± 0.2-month-old mutant mice or sibling controls were equilibrated in bath containing 4 mM [K$^+$], and 1.3 mM [Ca$^{2+}$], and stimulated as in Figure 6; normalized peak tetanic responses (mean ± SEM) are shown. (A) Mutant EDL was highly sensitive to 0.5–2.0 μM ouabain, which affected control muscle much more slowly. (B) Adding 0.5 μM ouabain greatly exacerbated the force reduction caused by raising [K$^+$] to 8 mM (compare Figure 6B) and produced sustained weakness. (C) Adding 0.5 μM ouabain upon raising [K$^+$] to 10 mM not only produced rapid paralysis that was reversible in the recovery solution but also nearly abolished the partial rebound that had occurred after 7 minutes in Figure 6C. Gray bars indicate significant differences by ANOVA ($P < 0.05$) between mutant (red circles) and control (open squares) responses. ANOVA was not determined in A during 40–60 minutes because the ouabain concentration was different for mutant (0 μM) and control (2 μM).

**Slowed recovery of mutant EDL and susceptibility to delayed weakness after fatigue.** Because ionic shifts of Na$^+$ and K$^+$ associated with the postexercise state may trigger paralytic attacks in HyperKPP, we next compared the properties of mutant and control muscles after continuous activity. Fatigue of isolated EDL muscles was induced by continuous 100-Hz stimulation using 1-ms pulses under baseline ionic conditions of 4 mM [K$^+$], and 2 mM [Ca$^{2+}$], at 25°C. This produced a sustained contraction that began to weaken within several seconds (Figure 8A). In EDL muscle from older mice (~11 months), the time required for decline to 50% of the peak force (fatigue $T_{1/2R}$) was prolonged by 2.3-fold ($P < 0.001$) for mutant compared with control, while in muscle from younger mice (~4 months), the fatigue $T_{1/2R}$ was prolonged by 1.8-fold ($P < 0.001$) for mutant compared with control (Figure 8A). The observed increase in resistance to continuous stimulation for EDL muscle expressing mutant Na1.4 was consistent with the shift of fast muscles toward a more oxidative phenotype (Figure 4).

We next compared the ability of mutant and control EDL muscles to recover from the fatigue produced by 100-Hz stimulation (Figure 8B). Muscles from 8.5-month-old mice were first stimulated with 0.5-ms current pulses every 3 minutes at 125 Hz for 0.3 seconds and equilibrated in a bath containing 4 mM [K$^+$], and 1.3 mM [Ca$^{2+}$]. Fatigue stimulation at 100 Hz for 50 seconds (Figure 8B, blue box) produced a decline in force to less than 5% of the starting value for all muscles (indicated by the symbols at $t = 0$). The $T_{1/2R}$ for entry into fatigue was 12.0 ± 3.7 seconds for mutant and 6.1 ± 0.7 seconds for control EDL (data not shown, $P < 0.01$). When recovery proceeded in the same bath, the time required to regain 50% of the recovery amplitude from the fatigue-induced nadir (recovery $T_{1/2R}$) was prolonged by 2.8-fold ($P < 0.01$) for mutant compared with control muscle (Figure 8B). Much of this difference reflected a slower initiation of recovery for the mutant, since the recovery rate at its midpoint did not differ greatly between mutant (9.3% ± 2.1%/min) and control (12.4% ± 5.2%/min, $P = 0.21$). This was consistent with the longer period of contractile activity during the stimulation for mutant muscle, which should have produced greater intracellular accumulation of Na$^+$ and extracellular efflux of K$^+$ into the t tubules. Mutant muscle recovered fully in the bath containing normal [K$^+$].

However, when the same induction of fatigue was followed by recovery in a bath containing 10 mM [K$^+$], and 0.5 mM [Ca$^{2+}$], to
mimic a sustained elevation of interstitial [K+] during an attack of HyperKPP, the recovery of force was aborted after 10 minutes for mutant muscle and was followed by a sustained loss of force over the next 10 minutes (Figure 8C). In contrast, although the recovery of control muscle was also impaired, the force began to decline slowly only after 20 minutes. The weakness in high [K+] bath containing 4 mM [K+] and 2 mM [Ca2+] was more vulnerable to sustained weakness during recovery in elevated [K+] compared with control muscle.

**Discussion**

We observed several distinctive features in mice harboring a mutation in the gene encoding Na1.4, corresponding to the human Met1592Val HyperKPP allele. First, skeletal muscle from Na1.4 mutant mice showed prominent electrical myotonia, fiber type switching to a more oxidative phenotype, and myopathic changes related to gene dosage and age. Second, isolated EDL muscle from heterozygous mutant (+/m) animals developed less tetanic force and exhibited slower relaxation compared with muscle from wild type (+/+ controls); these differences also increased with age. Third, rapid and sustained weakness of mutant EDL muscle was induced upon exposure to 10 mM [K+] that could be exacerbated by lowering [Ca2+] and by partial inhibition of the Na+/K+ pump. Fourth, the weakness of mutant muscle was rapidly and fully reversed upon restoration of normal [K+] and elevation of [Ca2+]. Fifth, mutant EDL muscle fatigued at a slower rate but also recovered more slowly than did control muscle. Weakness was reversible in recovery buffer, and mutant muscles regained force more slowly than did control muscles. The time required for regain of the peak force (fatigue T1/2%) was increased by 2.8-fold for mutant compared with control. (B) Recovery from fatigue for EDL muscles from 8.5 ± 0.4-month-old mutant (n = 6) and sibling controls (n = 5) in normal [K+]. Tetanic stimuli (0.5-ms, 70-mA current pulses for 300 ms at 125 Hz) were applied before and after 100-Hz stimulation (small blue box), and the normalized responses (mean ± SEM) are shown. The time required to regain 50% of the full extent of recovery (recovery T1/2%) was increased by 2.8-fold for mutant compared with control. (C) Stimulation of EDL muscles to fatigue as in B was followed by exposure to a bath containing 10 mM [K+] and 0.5 mM [Ca2+], which impaired the extent of recovery for mutant more than control muscles. Weakness was reversible in recovery buffer, and mutant muscles regained force more slowly than did control muscle. Gray bars in the left panels indicate significant differences by ANOVA (P < 0.05) between mutant (red circles) and control (open squares) responses. The bar graphs in the right panels show mean ± SEM. *P < 0.005, 2-tailed Student’s t test.

**Figure 8**

Mutant (+/m) EDL fatigued more slowly than control (+/+ muscle) and was more vulnerable to impaired recovery in elevated [K+]. (A–C) Fatigue was induced by continuous 100-Hz stimulation to isolated EDL muscles using 1-rns pulses in bath that contained 4 mM [K+] and 2 mM [Ca2+]. (A) In the left panel, tetanic force was normalized to the peak value, and the responses (mean ± SD, dashed lines) are shown for EDL from (+/m) mice (n = 8, 10.8 ± 2.2 months old) or (+/+ mice) (n = 5, 11.4 ± 1.8 months old). The time required for decline to 50% of the peak force (fatigue T1/2%) was increased by 2.3-fold for the older mutant mice versus controls and by 1.8-fold for younger mutant mice (n = 6, 4.0 ± 0.7 months old) versus controls (n = 10, 4.2 ± 0.8 months old). (B) Recovery from fatigue for EDL muscles from 8.5 ± 0.4-month-old mutant (n = 6) and sibling controls (n = 5) in normal [K+]. Tetanic stimuli (0.5-ms, 70-mA current pulses for 300 ms at 125 Hz) were applied before and after 100-Hz stimulation (small blue box), and the normalized responses (mean ± SEM) are shown. The time required to regain 50% of the full extent of recovery (recovery T1/2%) was increased by 2.8-fold for mutant compared with control. (C) Stimulation of EDL muscles to fatigue as in B was followed by exposure to a bath containing 10 mM [K+] and 0.5 mM [Ca2+], which impaired the extent of recovery for mutant more than control muscles. Weakness was reversible in recovery buffer, and mutant muscles regained force more slowly than did control muscle. Gray bars in the left panels indicate significant differences by ANOVA (P < 0.05) between mutant (red circles) and control (open squares) responses. The bar graphs in the right panels show mean ± SEM. *P < 0.005, 2-tailed Student’s t test.
characteristic of late-stage HyperKPP (7). The latter changes were accelerated in young (m/m) mice despite no spontaneous bouts of episodic paralysis.

A shift in the fiber type composition toward more oxidative type IIA fibers is consistent with the effect of continuous muscular activity produced by chronic stimulation (31) and would also be expected from the myotonic activity observed in this study. Gene expression in specific fiber types is coordinately controlled by transcription factors (31). One of these factors, PGC-1α, increases oxidative capacity in muscles and was upregulated in mutant tibialis anterior muscle (Figure 4G). Thus, the muscle from mutant mice and HyperKPP share a myotonic phenotype, and the resulting shift in fiber type and upregulation of at least one transcription factor are consistent with the expected consequences of chronic muscle activity.

The decrease in twitch and tetanic force concomitant with slower relaxation for mutant compared with control EDL further suggested that the contractile characteristics were shifted toward those of a slow-twitch muscle like soleus, which generates less force and relaxes more slowly than normal EDL (41). It is important to note, however, that the decrease in force generation with aging in the mutant mice may also be in part related to the increased number of damaged fibers. Regardless of the mechanism for the lower force, it is analogous to the clinical observation of increasing fixed weakness (or lower force generation) with age in HyperKPP patients (10, 14) and supports the notion that myopathy may remain normal (3.5–5.0 mM) in up to 50% of individuals during attacks. The muscle interstitial [K\(^+\)] remained in the normal range during attacks. The decrease in twitch and tetanic force concomitant with slower relaxation for mutant compared with control EDL further suggested that the contractile characteristics were shifted toward those of a slow-twitch muscle like soleus, which generates less force and relaxes more slowly than normal EDL (41). It is important to note, however, that the decrease in force generation with aging in the mutant mice may also be in part related to the increased number of damaged fibers. Regardless of the mechanism for the lower force, it is analogous to the clinical observation of increasing fixed weakness (or lower force generation) with age in HyperKPP patients (10, 14) and supports the notion that myopathy may remain normal (3.5–5.0 mM) in up to 50% of individuals during attacks. The muscle interstitial [K\(^+\)] remained in the normal range during attacks. The decrease in twitch and tetanic force concomitant with slower relaxation for mutant compared with control EDL further suggested that the contractile characteristics were shifted toward those of a slow-twitch muscle like soleus, which generates less force and relaxes more slowly than normal EDL (41). It is important to note, however, that the decrease in force generation with aging in the mutant mice may also be in part related to the increased number of damaged fibers. Regardless of the mechanism for the lower force, it is analogous to the clinical observation of increasing fixed weakness (or lower force generation) with age in HyperKPP patients (10, 14) and supports the notion that myopathy may remain normal (3.5–5.0 mM) in up to 50% of individuals during attacks. The muscle interstitial [K\(^+\)] remained in the normal range during attacks.

Elevated [K\(^+\)]\(_o\) produced sustained weakness of isolated mutant EDL muscle. Individuals with HyperKPP typically develop profound weakness when venous [K\(^+\)] is only 4.5–6.5 mM, and the venous [K\(^+\)] can remain normal (3.5–5.0 mM) in up to 50% of individuals during paralytic episodes (14, 42). The original “normokalemic” periodic paralysis family described by Poskanzer and Kerr (43) and subsequently shown to harbor the Met1592Val mutation in the Na\(^+\)/K\(^+\) pump (31) in the Na\(^+\)/K\(^+\) pump mutation can be heterogeneous, though, with other reports indicating attacks of weakness in mutants (31). One of these factors, PGC-1α, increases oxidative capacity in muscles and was upregulated in mutant tibialis anterior muscle (Figure 4G). Thus, the muscle from mutant mice and HyperKPP share a myotonic phenotype, and the resulting shift in fiber type and upregulation of at least one transcription factor are consistent with the expected consequences of chronic muscle activity.

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Elevated [Ca\(^{2+}\)]\(_o\) produces sustained weakness of isolated mutant EDL muscle. Individuals with HyperKPP typically develop profound weakness when venous [K\(^+\)] is only 4.5–6.5 mM, and the venous [K\(^+\)] can remain normal (3.5–5.0 mM) in up to 50% of individuals during paralytic episodes (14, 42). The original “normokalemic” periodic paralysis family described by Poskanzer and Kerr (43) and subsequently shown to harbor the Met1592Val mutation in the Na\(^+\)/K\(^+\) pump (31) in the Na\(^+\)/K\(^+\) pump mutation can be heterogeneous, though, with other reports indicating attacks of weakness in mutants (31). One of these factors, PGC-1α, increases oxidative capacity in muscles and was upregulated in mutant tibialis anterior muscle (Figure 4G). Thus, the muscle from mutant mice and HyperKPP share a myotonic phenotype, and the resulting shift in fiber type and upregulation of at least one transcription factor are consistent with the expected consequences of chronic muscle activity.

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In conclusion, knock-in mice expressing the human Met1592Val mutation in the gene encoding Nav1.4 exhibit several hallmarks of the HyperKPP phenotype. These include: myotonic activity in vivo, increased myofiber damage, increased sensitivity to elevated $[K^+]_o$, resulting in profound weakness, increased capacity to recover from $K^+$-induced weakness upon increasing $[Ca^{2+}]_o$, and apparent weakness following fatigue when the recovery occurs at elevated $[K^+]_o$. Moreover, this study provides several new mechanistic insights relevant to the pathophysiology of HyperKPP. First, we have shown that induction of sustained muscle weakness requires a local elevation of $[K^+]_o$, to a level that exceeds the serum $[K^+]_o$ attained during attacks. Second, we have demonstrated a modulatory effect of $[Ca^{2+}]_o$ on $K^+$-induced weakness that extends beyond the clinical observation of improvement with calcium gluconate.

Third, we have shown an increased susceptibility to paralysis leading to the curious delay (10–30 minutes) between provocative exercise and onset of weakness in human HyperKPP. Fourth, we have shown that induction of sustained muscle weakness requires increased mutant gene dosage has and onset of weakness following fatigue when the recovery occurs at elevated $[K^+]_o$. Moreover, this study provides several new mechanistic insights relevant to the pathophysiology of HyperKPP. First, we have shown that induction of sustained muscle weakness requires a local elevation of $[K^+]_o$, to a level that exceeds the serum $[K^+]_o$ attained during attacks. Second, we have demonstrated a modulatory effect of $[Ca^{2+}]_o$ on $K^+$-induced weakness that extends beyond the clinical observation of improvement with calcium gluconate.

Methods

Mice. Mutant Nav1.4 knock-in mice were generated as detailed in Supplemental Methods at the Massachusetts General Hospital Knock-in Mouse Core facility directed by En Li. The line was bred into the C57BL/6J background for more than 4 generations and has been designated B6.129S4—Snck1tm12K. All procedures were conducted under protocols approved by the Institutional Animal Care and Use Committees at Massachusetts General Hospital and the University of Massachusetts Medical School in accordance with the Animal Welfare Act and the Department of Health and Human Services.

Southern blotting. Genomic DNA was digested as indicated, run on 0.8% agarose gels, and transferred to nylon membranes using standard protocols. Prehybridization was at 45°C for 2 hours in buffer A, containing 2.8× SSPE, 50% formamide, 5× Denhardt’s, and 50 μg/ml denatured salmon sperm DNA. DNA probes were labeled with $[^32P]dGTP$ using the Random Primed DNA Labeling Kit (Boehringer) and added at 2 × 10^6 cpm/ml to buffer A. Blots were hybridized overnight at 42°C, washed 4 times at 50°C with increasing stringency (final 0.2× SSC plus 1% SDS), and bands were visualized by autoradiography.

Total RNA isolation and RT-PCR. Flash-frozen skeletal muscle, heart, and brain tissues (100–200 mg) from +/- and +/-m mice were homogenized in 2 ml of TRIzol (Gibco BRL) using a Polytron PT 10-35 homogenizer (Kinematica AG). The homogenized samples were incubated for 5 minutes at room temperature and centrifuged at 12,000 g for 10 minutes at 4°C. The upper phase was extracted with 0.4 ml of chloroform for 15 seconds, incubated at room temperature for 3 minutes, and centrifuged at 12,000 g for 15 minutes at 4°C. The upper aqueous phase was mixed with 1 ml of isopropl alcohol, incubated at room temperature for 10 minutes, and centrifuged at 12,000 g for 10 minutes. The pellet was washed with 2 ml of 75% ethanol by centrifuging at 7,500 g for 5 minutes at 4°C. The RNA pellet was air dried for 10 minutes and resuspended in RNase-free H2O.

For first-strand cDNA synthesis for RT-PCR, 1.5 μg of total RNA and 2 μl of random decamers (50 μM; Ambion) were adjusted to 12 μl with RNase-free H2O and heated to 80°C for 3 minutes to denature the RNA. The RNA-primer mixture was chilled on ice and centrifuged briefly. The remaining components for reverse transcription were added, including 2 μl of 10× first-strand buffer (500 mM KCl, 15 mM MgCl2, and 100 mM Tris-HCl, pH 8.3), 4 μl of dNTP mix (2.5 mM each dNTP), 1 μl of RNase inhibitor (10 U/μl; Ambion), and 1 μl of MMLV-RT (100 U/μl; Ambion). The reaction was incubated for 60 minutes at 42°C followed by 10 minutes at 92°C to inactivate the reverse transcriptase. PCR was performed as above for amplification of genomic DNA using the standard protocol, except that the reaction contained 4 μl of reverse transcription products as template, and the annealing temperature was 60°C. For the RT-PCR in Figure 2B, the template primers were (c) mSk757F, 5′-TACTACTCCATGGGCCGCT-GGAATATCTTCGACTTCG-3′ at the 3′ end of exon 23 and (b) mSk998R, 5′-CTGAGCAATCTCATCATCCTCAGC-3′ in the 3′-UTR of exon 24. This produced a 1.43-kb DNA product amplified only from cDNA that was digested with Hpal or NptI as above.

Northern blotting. Total RNA (5 μg) from mouse tissues was denatured for 15 minutes at 65°C in 3 volumes of formaldehyde load dye (Ambion) and separated on a 1% formaldehyde agarose gel (NorthernMax; Ambion). The RNAs were transferred to nylon membrane, crosslinked, and prehybridized in UltraHyb buffer (Ambion) for more than 30 minutes at 42°C. The mSkE24 DNA probe was labeled with $[^32P]dCTP$, denatured for 10 minutes at 95°C, chilled for 5 minutes on ice, added into UltraHyb buffer, and incubated with the blot for 16–24 hours at 42°C. The blot was washed with low-high-stringency wash solutions (Ambion) at 42°C and exposed to BioMax MR film (Kodak). Hybridization of a GADPH probe (Ambion) was similarly performed after probe removal using the Strip-EZ DNA kit (Ambion).

Antibodies. Primary antibodies included a monoclonal antibody generously provided by Susan D. Kramer (University of Kentucky, Lexington, Kentucky, USA) (L/D3, dilution 1:30), which specifically recognizes Na1.4 (19); a rabbit polyclonal antibody that recognizes the C terminus of PGC-1 (AB3242, Chemicon; dilution 1:1,000) (59); and a rabbit polyclonal antibody that recognizes GADPH (ab9485, Abcam; dilution 1:2,000). Secondary antibodies were HRP-conjugated reagents from Amersham (dilution 1:1,000) that included rabbit anti-mouse IgG (NIF 825) or donkey anti-rabbit Ig (NA 934). The A4.74 monoclonal antibody developed by H. M. Blau that specifically recognizes myosin in type IIA fatigue-resistant fast-twitch fibers (35) was obtained from the Developmental Studies Hybridoma Bank developed under the auspices of the NICHD and maintained by the University of Iowa, Department of Biological Sciences, Iowa City, Iowa, USA.

Protein isolation and Western blotting. Membrane protein fractions (Figure 2C) were obtained by disruption of 0.2 g of frozen tissue using a Polytron homogenizer for 30–60 seconds on ice in a 70-fold (wt/wt) excess of lysis buffer (pH 7.6) that contained 0.25 M sucrose, 100 mM Tris, 10 mM EDTA, 10 mM EGTA, and 1× protease inhibitor cocktail (Complete; Roche). The mixture was centrifuged at 1,900 g for 5 minutes at 4°C, and the supernatant was collected and spun further at 22,000 g for 30 minutes at 4°C. The pellet was resuspended in 0.8 ml of water, 40 μl of 20% SDS was added, and the mixture was heated for 20 minutes at 65°C.
Soluble proteins (Figure 4G) were obtained by disruption of frozen tissues at 4°C in a 10-fold (wt/vol) excess of lysis buffer (pH 7.6) that contained 8.7 mM NaH$_2$PO$_4$, 58 mM Na$_2$HPO$_4$, 144 mM NaCl, 1% NP-40, 0.5% sodium deoxycholate, 0.1% SDS, and 1× protease inhibitor cocktail, using a PRO 200 homogenizer (PRO Scientific). Samples were centrifuged at 22,000 g for 10 minutes at 4°C, and the final supernatant after 2 spins was collected. All proteins were stored as aliquots at –80°C and concentrations were determined by the BCA assay (Pierce).

For Western blots, proteins were resolved on 7.5% SDS-PAGE and electroblotted to PVDF membranes. The membrane was blocked with 1% non-fat milk in 137 mM NaCl, 2.7 mM KCl, 25 mM Tris-HCl (pH 7.4) for 30 minutes, followed by addition of primary antibody and incubation with gentle rocking overnight at 4°C (or 2 hours at room temperature for 30 minutes, followed by addition of primary antibody and incubation for 2 hours at room temperature). Blots were washed 3 times for 5 minutes each with TBS plus 0.1% Tween-20 (TBS-T) and then incubated with the appropriate secondary antibody (dilution 1:1,000) in blocking solution for 60 minutes for the L/D3 antibody). Blots were washed 3 times for 5 minutes each with TBS-T and then incubated with the appropriate secondary antibody (dilution 1:1,000) in blocking solution for 60 minutes at room temperature. After 3 washes for 5 minutes each with TBS-T, the immunoreactive proteins were visualized by detection of HRP-catalyzed chemiluminescence (ECL kit; Amersham) and imaged using a Kodak ImageStation 440CF. Protein bands were quantitated using ImageJ software (http://rsb.info.nih.gov/ij/).

**Muscle staining**. Standard protocols were used to stain 10-μm muscle sections using H&E, SDH, and the A4.74 antibody, as detailed in Supplemental Methods.

**Electromyography**. Mice were anesthetized with 40 mg/kg sodium pentobarbital by intraperitoneal injection. Surface temperature was monitored throughout the experiment and kept above 30°C by using a heated pad underneath the mouse and a heat lamp above the mouse. Spontaneous electrical activity of hind-limb muscles was recorded using 25-mm bipolar concentric needles (Oxford Instruments) and a ground electrode taped to the tail.

**Muscle twitch force measurements**. Mice were anesthetized with isoflurane by inhalation and killed by cervical dislocation. The EDL muscle was dissected and mounted vertically in a 25-ml organ bath (World Precision Instruments). The starting bath solution for Figure 5, Figure 8A, and Supplemental Figure 1 contained (in mM): 118 NaCl, 25 NaHCO$_3$, 2.82 KCl, 1.18 KH$_2$PO$_4$, 1.18 MgSO$_4$, 2.0 CaCl$_2$, 10 glucose (Humulin U-100; Lilly, 20 U/I), and 2.82 µl tubocurarine chloride (0.25 mg/ml) and was bubbled continuously with 95% O$_2$, 5% CO$_2$. The bath temperature was maintained at 35°C to prolong muscle viability. The muscles were adjusted to 2.7 mm apart. Isometric contractile responses were recorded using a force transducer, acquired at 2 kHz, and analyzed using PClab9 (Axon, Origin MicroCal), and StatView (SAS) software.

**Statistics**. Data are presented as mean ± SEM unless otherwise indicated. Two-tailed Student’s t test was used to compare the means between 2 groups. The temporal responses in Figures 6–8 were compared by repeated-measures ANOVA followed by Bonferroni’s post-hoc test. Significance was accepted for P < 0.05.

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