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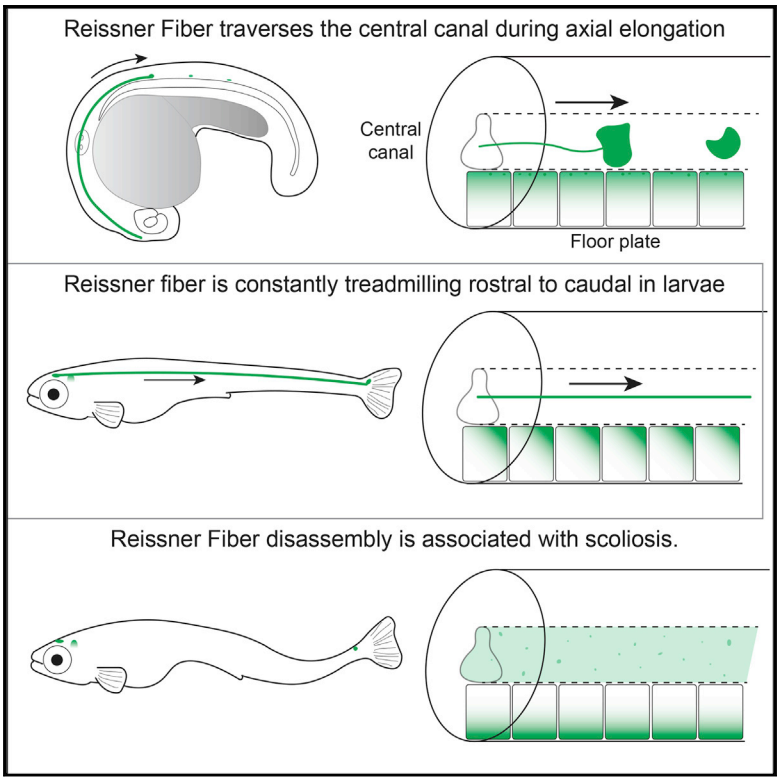
The Reissner Fiber Is Highly Dynamic *In Vivo* and Controls Morphogenesis of the Spine

Graphical Abstract



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In Brief

Troutwine et al. report a new *scospondin-GFP* knockin zebrafish strain and demonstrate intriguing dynamic properties of the Reissner fiber in the brain and central canal *in vivo*. Using forward genetics and cell biological approaches, they demonstrate that Reissner fiber assembly is critical during spine morphogenesis in zebrafish.

Highlights

- Hypomorphic *scospondin* mutants show disassembly of the Reissner fiber and scoliosis
- SCO-spondin mislocalization in floor plate cells is associated with fiber loss
- A *scospondin-GFP* knockin strain reveals dynamic properties of Reissner fiber *in vivo*
- Loss of the Reissner fiber is a common feature of scoliosis in zebrafish

Troutwine et al., 2020, Current Biology *30*, 2353–2362
June 22, 2020
https://doi.org/10.1016/j.cub.2020.04.015

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The Reissner Fiber Is Highly Dynamic *In Vivo* and Controls Morphogenesis of the Spine

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https://doi.org/10.1016/j.cub.2020.04.015

SUMMARY

Cerebrospinal fluid (CSF) physiology is important for the development and homeostasis of the central nervous system, and its disruption has been linked to scoliosis in zebrafish [1, 2]. Suspended in the CSF is an extracellular structure called the Reissner fiber, which extends from the brain through the central canal of the spinal cord. Zebrafish *scospondin*-null mutants are unable to assemble a Reissner fiber and fail to form a straight body axis during embryonic development [3]. Here, we describe hypomorphic missense mutations of *scospondin*, which allow Reissner fiber assembly and extension of a straight axis. However, during larval development, these mutants display progressive Reissner fiber disassembly, which is concomitant with the emergence of axial curvatures and scoliosis in adult animals. Using a *scospondin-GFP* knockin zebrafish line, we demonstrate several dynamic properties of the Reissner fiber *in vivo*, including embryonic fiber assembly, the continuous rostral to caudal movement of the fiber within the brain and central canal, and subcommissural organ (SCO)-spondin-GFP protein secretion from the floor plate to merge with the fiber. Finally, we show that disassembly of the Reissner fiber is also associated with the progression of axial curvatures in distinct scoliosis mutant zebrafish models. Together, these data demonstrate a critical role for the Reissner fiber for the maintenance of a straight body axis and spine morphogenesis in adult zebrafish. Our study establishes a framework for future investigations to address the cellular effectors responsible for Reissner-fiber-dependent regulation of axial morphology.

RESULTS AND DISCUSSION

Adolescent idiopathic scoliosis (AIS) is a common disorder causing curvature of the spine. Despite accumulating evidence pointing to its heritable nature, the underlying genetic causes of AIS are thought to be complex and heterogeneous and thus far are not well established. Zebrafish mutants in motile cilia components with disruption of cerebrospinal fluid (CSF) flow also demonstrate scoliosis, resembling AIS [1, 2]. For example, the expression of AIS-associated variants of the centrosomal protein gene *POC5* led to cilia defects in cell culture and spine deformities in zebrafish [4, 5]. How motile cilia and CSF flow contribute to the pathogenesis of scoliosis in these models remains unresolved.

The Reissner fiber (RF) is an enigmatic glycoprotein thread suspended in CSF, which stretches from the brain down the central canal, where it terminates at the base of the spinal cord [6, 7]. The fiber is largely composed of the glycoprotein subcommissural organ (SCO)-spondin [8], which is expressed and secreted from the SCO of the brain and from the floor plate at the ventral midline of the spinal cord [9, 10]. In zebrafish, *scospondin*-null mutants fail to secrete and assemble a RF and fail to develop a straight body axis during embryonic development [3]. The failure to straighten the body axis or "curled tail down" phenotype has long been observed in zebrafish mutants with disrupted motile cilia physiology [11–13], many of which also exhibit defects in RF assembly [3]. Despite the clear association of the RF with morphogenesis of a straight body axis, it is not yet clear how disruptions of these processes regulate spine morphogenesis during larval development and in adults.

Hypomorphic Mutations of *Scospondin* Lead to Progressive Scoliosis in Zebrafish

In a forward genetic screen for adult-viable scoliosis mutant zebrafish (unpublished data), we found two non-complementing scoliosis mutant zebrafish lines (Figures 1B, 1B', and S1B–S1E). Using whole-genome- or whole-exome-based sequencing, mapping, and variant calling (Figures S1H and S1I), we identified

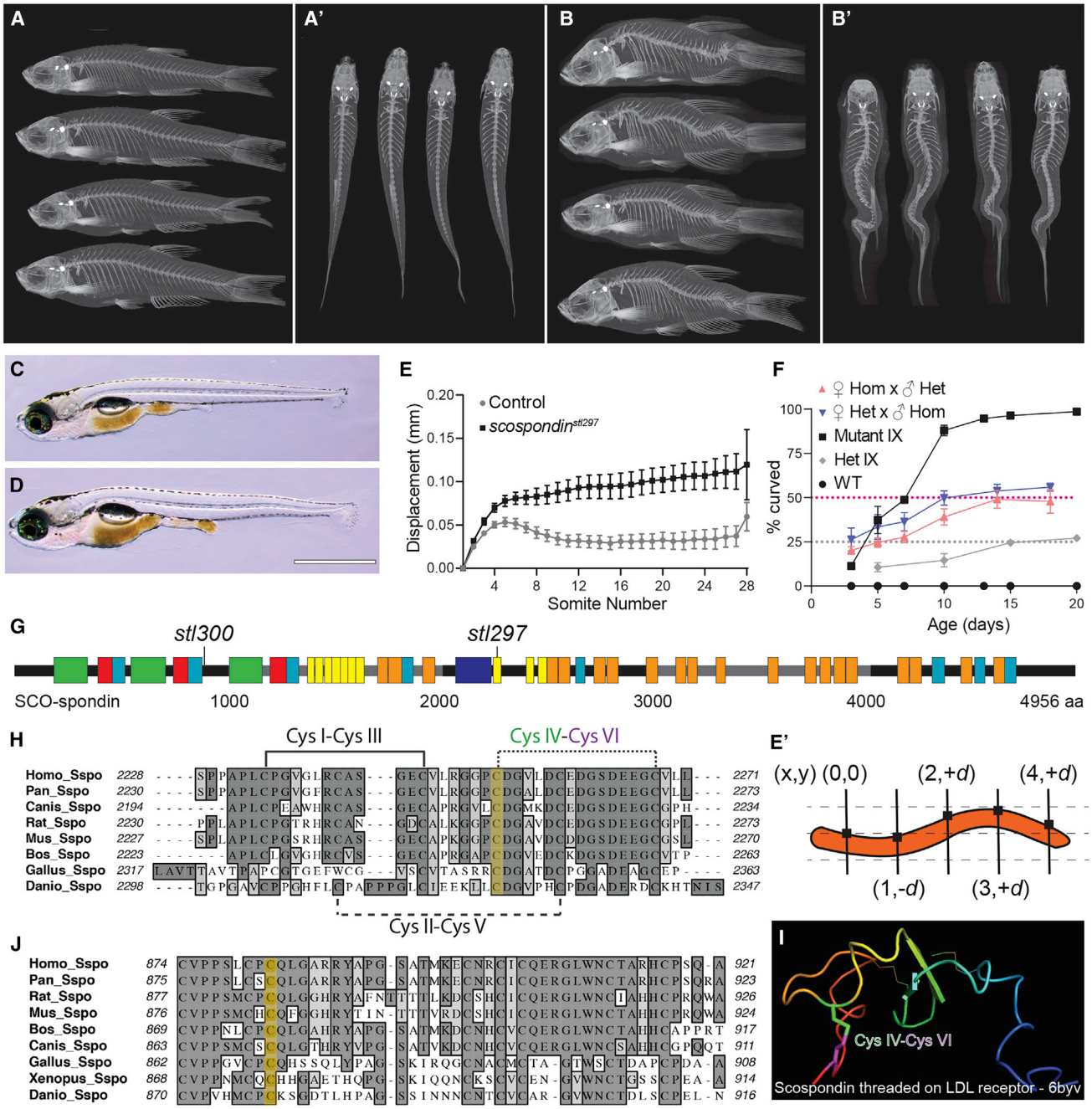

Figure 1. Hypomorphic Mutations of *Scospondin* Lead to Progressive Scoliosis in Zebrafish

(A–B') MicroCT images of *scospondin*$^{stl300/+}$ (A and A') and *scospondin*$^{stl300/stl300}$ mutant zebrafish (B and B') at 90 dpf, in both lateral (A and B) and dorsal (A' and B') views showing adult-viable scoliosis.

(C and D) Bright-field image of the typical straight body of a wild type (C) and atypical axial curvatures observed in homozygous *scospondin*$^{stl297/stl297}$ mutant (D) larvae at 13 dpf. Scale bar, 1 mm.

(E) Dorsal-ventral axis displacement of the notochord in 5-dpf heterozygous *scospondin*$^{stl297/+}$ and *scospondin*$^{stl297/stl297}$ mutants (mean + SEM, n = 10 and 23, respectively). (E') Displacement is the absolute value of the dorsal-ventral (y axis) measured against an origin set at the intersection of the first somite boundary and the dorsal edge of the notochord and propagated along the entire axis at each somite boundary for each animal.

(F) Incidence of axial curvatures over developmental time for wild type, *MZscospondin*^{stl297}, and progeny from heterozygous *scospondin*$^{stl297/+}$ × *scospondin*$^{stl297/stl297}$ mutant crosses from both female and male homozygotes and progeny from heterozygous *scospondin*$^{stl297/+}$ incrosses (mean + SEM; n = 112, 105, 116, 138, and 118 embryos, respectively, pooled from three independent clutches).

(G) Schematic representation of zebrafish SCO-spondin protein, demarking the location of the *scospondin* alleles causing scoliosis in zebrafish reported in this study. Boxes represent conserved motifs; legend in Figure S1.

(legend continued on next page)

two recessive missense alleles of the *scospondin* gene, *scospondin*^{stl297} and *scospondin*^{stl300}, which both disrupt evolutionarily conserved cysteine residues at independent regions of the protein (Figures S1J–S1L). Progeny from *scospondin*$^{stl297/+}$ or *scospondin*$^{stl300/+}$ heterozygoous mutant fish were morphologically wild-type at 1 day post-fertilization (dpf); however, at 3 dpf, we observed the onset of progressive axial curvatures in a subset of these progeny (Figure 1F), which led to spine curvatures observed in the dorsal-ventral (Figures 1B and S1B) and medial-lateral (Figures 1B' and S1B') axes in adult fish. This scoliosis phenotype was observed without obvious vertebral malformation or alterations in the development of cartilage or bone in the axial skeleton (Figures S1C and S1D), resembling aspects of AIS in humans. Complementation testing between *scospondin*$^{stl297/+}$ and *scospondin*$^{stl300/+}$ heterozygotes resulted in putative transheterozygous *scospondin*$^{stl297/stl300}$ progeny manifesting curvatures of the body axis resembling those observed for each homozygous mutant outlined above (22.7%; n = 198; Figure S1E).

scospondin$^{icm13/icm13}$-null mutants display severe defects in axial straightening at 3 dpf and were not reported to be adult viable [3]. To further determine the nature of the *scospondin*^{stl297} and *scospondin*^{stl300} alleles, we crossed *scospondin*$^{stl297/+}$ heterozygous mutants to heterozygous *scospondin*$^{hsc105/+}$-null mutants, which phenocopy the axis straightening defect reported for *scospondin*$^{icm13/icm13}$ mutant (*scospondin*^{hsc105} described in [14] in this issue of *Current Biology*). For the progeny resulting from these crosses, we observed no defects in straightening the body axis in embryos. Instead, putative transheterozygous *scospondin*$^{hsc105/stl297}$ mutant larvae displayed only mild axial curvatures at 15 dpf (27.1%; n = 236), which was identical to phenotypes observed in both zygotic and maternal zygotic *scospondin*$^{stl297/stl297}$ *and* *scospondin*$^{stl300/stl300}$ mutants (Figures 1D and S1E). Altogether, these results confirm that *scospondin*^{stl297} and *scospondin*^{stl300} are independent hypomorphic missense mutations of *scospondin*.

MicroCT analysis in developmentally matched adult zebrafish at 90 dpf revealed that *scospondin*$^{stl297/stl297}$ and *scospondin*$^{stl300/stl300}$ mutants exhibited abnormalities in bone morphology and mineralization (Figure S2). On average, patterns of sagittal and lateral displacements from midline were similar in both mutants yet more severe in posterior vertebrae (Figures S2B, S2C, S2B', and S2C'). Analysis of several measures of bone quality in both *scospondin*$^{stl297/stl297}$ and *scospondin*$^{stl300/stl300}$ mutants demonstrated increased bone deposition in the vertebrae in these mutants compared to heterozygous control animals for each allele. For more in-depth morphometric analysis of the spine, we used the FishCut analysis workflow on our microCT datasets [15]. First, we segmented 16 distinct vertebral bodies along the spine and each vertebra into the three elements: the centrum; the haemal arch; and the neural arch (Figure S2N'). Second, we quantified (1) vertebral mass, as total volume and thickness (Figures S2E–S2G, S2K–S2M, S2E'–S2G', and S2K'–S2M'), and (2) bone quality, as tissue mineral density in comparison to a hydroxyapatite (HA) standard (mgHA/cm3; Figures S2H–S2J and S2H'–S2J'). These data demonstrated an overall increase in vertebral mass and mineralization in both *scospondin*$^{stl297/stl297}$ and *scospondin*$^{stl300/stl300}$ mutant fish (Figure S2). We observed no change in centrum length comparing homozygous *scospondin* mutants and heterozygous controls (Figures S1D and S1D'), indicating that decreased body lengths observed in the mutant fish are attributable to spine curvature rather than shortened or compressed vertebrae. Analysis of *Z* scores for each of these morphometric measures of the vertebral bodies and spine demonstrated that *scospondin*$^{stl297/stl297}$ mutants display a more severe scoliosis (measured as sagittal and lateral displacement of the spine), although *scospondin*^{stl300} mutants exhibited increased bone volume and mineralization of the spine (Figures S2O and S2P). We suggest that this increase in bone deposition is a response to increased mechanical loading of the spine as the deformity progresses.

Prior to the onset of spine morphogenesis, we observed mild axial curvatures of the body and notochord in both *scospondin*$^{stl297/stl297}$ and *scospondin*$^{stl300/stl300}$ and transheterozygous *scospondin*$^{stl297/stl300}$ mutants (Figures 1D and S1E). To quantify the onset of body axis curvatures throughout development, we assayed a full complement of combinatorial crosses using both homozygous and heterozygous *scospondin*^{stl297} mutant animals to test whether maternal contributions of SCO-spondin would alter the onset of axial curvatures. For all crosses, regardless of maternal *scospondin* genotype, we observed the onset of progressive axial curvatures, which were first apparent at 3 dpf and fully penetrant at expected Mendelian ratios by 20 dpf (Figure 1F). Next, we asked whether the location of axial curvatures along the rostral-caudal axis was stereotyped in *scospondin*^{stl297} mutants. The absolute value of notochord displacement at each somite boundary was propagated along the entire axis in both *scospondin*$^{stl297/stl297}$ mutants and heterozygous controls (Figure 1E). We measured the dorsal-ventral displacement (y axis) against an origin established at the intersection of the first somite boundary and the dorsal edge of the notochord for each animal (Figure 1E'). In control larvae, we observed stereotyped axial morphology that corresponded with tight average values of displacement at each somite boundary (n = 10), which, when graphed, illustrated a stereotyped notochord shape consistently observed in wild-type larvae at 5 dpf (Figures 1C and 1E). In contrast, *scospondin*^{stl297} mutants showed wider ranges of phenotypes from straight body axis to more pronounced axial curvatures (Figure 1D), which was reflected as increased average displacement values along the rostral to caudal axis (n = 23). Together, these data demonstrate that the formation of axial curvatures is a progressive phenomenon in

(H and J) Protein alignments (Clustal-W) of SCO-spondin protein showing the sequence surrounding the amino acid residues (yellow highlight) affected by the *scospondin*^{stl297} (H) and the *scospondin*^{stl300} (J) mutations.

(I) A homology model of *Danio rerio* SCO-spondin threaded onto the LDLrA domain derived from an LDL receptor structure (PDB: 6byv). The predicted disulfide bond and labeled cysteine (Cys) residues are highlighted in (H) and (I).

See also Figures S1 and S2.

scospondin^{stl297} mutants and that the incidence of axial curvatures along the rostral-caudal axis is a stochastic process, not regionally localized.

Disassembly of the Reissner Fiber Due to Defects in Secretion from the Floor Plate Is Correlated with the Onset of Axial Curvatures in Zebrafish

Scospondin protein is a large, heavily glycosylated protein composed of several repeating, well-conserved domains, established early in phylogeny (Figures 1G and S1L) [10, 16]. *scospondin*^{stl297} mutant phenotype segregates with a T6784A (ENSDART00000097773.4) mutation (Figure S1J), predicted to alter an evolutionarily conserved cysteine 2262 to serine (C2262S) in one of the low-density lipoprotein (LDL) receptor domains of the SCO-spondin protein (Figures 1H and S1L). *scospondin*^{stl300} phenotype segregates with a T2635A mutation (Figure S1K), predicted to alter cysteine 879 to serine (C879S), which is a highly conserved cysteine adjacent to a trypsin inhibitor like cysteine-rich domain (Figures 1J and S1L). Homology modeling of the *Danio rerio* SCO-spondin protein sequence partially maps onto a crystal structure of very low-density lipoprotein receptor (PDB: 6byv). Analysis of the model suggests that the *scospondin*^{stl297} mutation could disrupt an evolutionarily conserved disulfide bond (CysIV-CysVI) of the LDL receptor type A motif (Figures 1H and 1I), shown to be involved in protein stability of the LDL receptor [17]. Homology modeling for the region containing the *scospondin*^{stl300} mutation was unsuccessful; however, this cysteine is also neighboring many other well-conserved cysteine residues in SCO-spondin, suggesting it may also have a role in disulfide bonding.

To observe the RF assembly in *scospondin* mutant zebrafish, we utilized an established antiserum raised against bovine RF (AFRU) [18], which labels the RF, the floor plate, and terminal ampulla region at the base of the spinal cord in zebrafish (Figures 2A and 2C). In contrast to *scospondin*$^{icm13/icm13}$ mutants, which fail to form a fiber at 3 dpf [3], *scospondin*$^{stl297/stl297}$ mutant embryos displayed no obvious defects in the assembly of the RF (Figure 2B; n = 8). However, at 5 dpf, several *scospondin*$^{stl297/stl297}$ mutants displayed a variety of defects of the RF (Figure 2F), including irregular punctate pattern (Figure 2E'), disassembled fiber with an occasional bolus of Reissner material (Figure 2E''), or disassembled fiber with diffuse AFRU staining (Figures 2D, 2D', and 2E'''). We also observed several *scospondin*$^{stl297/stl297}$ mutants displaying a normal fiber at 5 dpf (Figure 2E). *scospondin*$^{stl297/+}$ larvae showed no changes in RF expression at 5 dpf (n = 16; Figures 2C and 2C'). Interestingly, the presence of an intact RF in *scospondin*$^{stl297/stl297}$ mutants was directly correlated with a straight body axis at 5 dpf; in contrast, defects in the RF were directly correlated with the mild to severe axial curvatures in these mutants. At 10 dpf, *scospondin*$^{stl297/+}$ heterozygous mutant larvae (100%; n = 8) displayed a straight body axis with an intact RF (Figures 2G and 2H). In contrast, *scospondin*$^{stl297/stl297}$ mutants displayed diffuse AFRU staining, without a RF (100%; n = 8; Figures 2I and 2J). Interestingly, we observed apical localization of AFRU-stained Reissner material in floor plate cells in heterozygous *scospondin*$^{stl297/+}$ (n = 8) and *scospondin*$^{stl300/+}$ (n = 7) larvae at 10 dpf (Figures 2G', 2H, and S1F). In contrast, we consistently observed the Reissner material localization at the basal surface of floor plate cells in both *scospondin*$^{stl297/stl297}$ (n = 8) and *scospondin*$^{stl300/stl300}$ (n = 6) mutants at 10 dpf (Figures 2I and S1G). These data suggest that disassembly of the RF in the two hypomorphic *scospondin* mutants may be in part due to disrupted secretion of Reissner material from the floor plate.

Zebrafish mutants that fail to form a floor plate display defects of RF assembly within the central canal, but not within the SCO [19]. We have shown that mutation of two independent, evolutionarily conserved cysteine residues in SCO-spondin led to disassembly of the RF, axial curvatures in larval fish, and AIS-like scoliosis in adults. We hypothesize that the apical to basal switch in Reissner material polarity in the floor plate cells is the result of disrupted disulfide bonding within the protein leading to unfolded mutant SCO-spondin, which impedes SCO-spondin/Reissner material secretion from the SCO and floor plate, preventing normal RF assembly. Altogether, these data suggest that the RF has a continuous and instructive role in axial straightness and spine morphogenesis in zebrafish.

Dynamic Properties of the Reissner Fiber Revealed in *Scospondin-GFP*^{ut24} Knockin Zebrafish

To monitor the dynamic properties of the RF during development, we engineered an endogenous C-terminal GFP gene fusion of *scospondin* in zebrafish. In brief, we used CRISPR/Cas9 to generate a targeted double-strand break within the last exon of the *scospondin* gene and an EGFP donor cassette with homology arms for in-frame C-terminal tagging (Figure S3A). From the resulting adult F0 fish, we isolated a single founder male by (1) PCR screening for EGFP sequence in genomic DNA from isolated sperm samples, (2) by confocal imaging of outcrossed progeny, and (3) by colocalization with AFRU immunofluorescence (Figures S3F–S3H; see STAR Methods). Imaging of our established stable line (*scospondin-GFP*^{ut24}) showed SCO-spondin-GFP expression *in vivo* labeling of the laser straight RF extending from the SCO in the brain, extending down the central canal and terminating at the base of the spinal cord at 3 dpf (Figures S3B and S3B'). This endogenous SCO-spondin-GFP expression mirrors previously reported tissue-specific expression patterns in zebrafish using RF antibodies and whole-mount *scospondin* gene expression [3, 10]. In our hands, SCO-spondin-GFP expression observed in *scospondin-GFP*^{ut24}, knockin zebrafish displayed tight colocalization (Pearson's R value, 0.98) with the AFRU antiserum labeling [18] (Figures S3F–S3H). High-magnification confocal time-lapse imaging of the floor plate in *scospondin-GFP*^{ut24} embryos demonstrated active secretion of SCO-spondin-GFP from the floor plate to merge with the RF (Figure S3I; Video S1), which supports a critical role for the floor plate in RF assembly during larval development. These observations also suggest that defects in apical localization of the AFRU-labeled Reissner material in *scospondin*^{stl297} mutants (Figure 2I') may be driving progressive disassembly of the RF. In the head, we observed SCO-spondin-GFP expression in the SCO and in the flexural organ, with the RF joining these two organs (Figures 3A, 3A', S3C, and S3C'). In the tail, we detected SCO-spondin-GFP expression in the floor plate and the RF ending as a coiled mass within the terminal ampulla at the base of the spinal cord (Figures 3C, 3C', and S3B'). We observed SCO-spondin-GFP-labeled RF

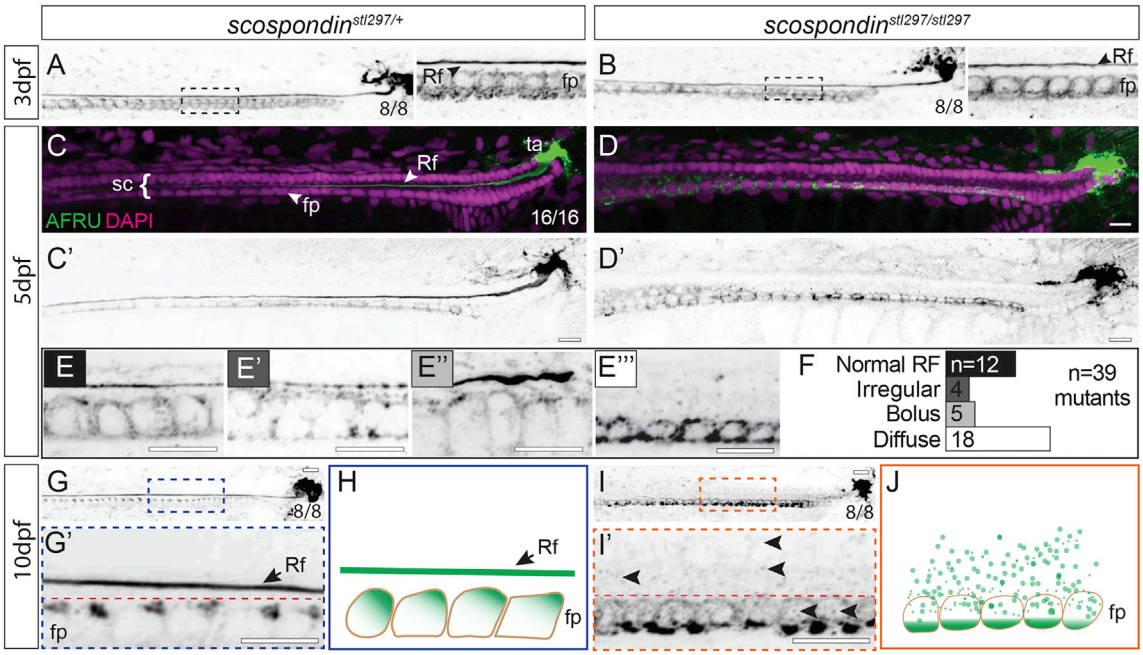

Figure 2. Disassembly of the Reissner Fiber due to Defects in Secretion from the Floor Plate Is Correlated with the Onset of Axial Curvatures in Zebrafish

Maximal Z projections of confocal stacks of the caudal region of the tail and spinal cord immunostained against the Reissner fiber in *scospondin*$^{stl297/+}$ and *scospondin*$^{stl297/stl297}$ mutants at 3 dpf (A and B), 5 dpf (C–F), and 10 dpf (G, G', I, and I'). Rf, Reissner fiber; fp, floor plate; sc, spinal cord; ta, terminal ampulla. (A and B) At 3 dpf, both heterozygotes (A) and mutants (B) have an assembled Reissner fiber (8/8 each genotype). Insets to the right of (A) and (B) highlight a magnified region (dashed box).

(C–E''') Pseudocolored merge from maximal Z projections of confocal stacks showing Reissner fiber (green) and DAPI (magenta) marking nuclei (C and D) and inverted grayscale image of Reissner fiber at 5 dpf (C' and D'). We observed the Reissner fiber in all heterozygous mutants (100%; n = 16; C), but the *scospondin*$^{stl297/stl297}$ showed some with the fiber (31%; n = 39) and some with a fiber in various stages of disassembly (69%; n = 39; D). We classified Reissner fiber staining as normal (E), irregular (E'), bolus (E''), or diffuse (E''') and counted the number of mutants in each class (F). Scale bars, 10 μm.

(G and I) At 10 dpf, we observed the Reissner fiber in all heterozygous controls (G), which was completely lost in the mutants (I; 100%; n = 7 and 8, respectively). Scale bars, 10 μm.

(H and J) Schematic representation of Reissner material localization at 10 dpf. In wild-type or heterozygous animals, Reissner material localizes to the apical surface of floor plate cells and is assembled into a Reissner fiber (H). In *scospondin*$^{stl297/stl297}$ mutants, the Reissner fiber is missing and Reissner material localizes at the basal portion of the floor plate (J).

See also Figures S1 and S2.

and terminal ampulla in young adult fish (60 dpf; Figures S3D and S3D'), suggesting that the RF functions through the life cycle in zebrafish.

To define the natural history of the RF assembly during embryonic development, we used confocal time-lapse imaging of *scospondin-GFP*$^{ut24/+}$ embryos from the early tailbud stage (~17 h post-fertilization [hpf]). We first observed the assembly of short SCO-spondin-GFP fibers at the rostral portions of the spinal canal between 20 and 24 hpf (red bracket, Figure 3F; Video S2), which could rapidly extend more caudally (red bracket, Figures 3G and 3H). SCO-spondin-GFP puncta were also observed to travel in a rostral to caudal direction (red arrows, Figures 3I and 3J) and appeared to join with other SCO-spondin-GFP material at the end of the spinal cord (Figure 3K). Imaging of this process at higher magnification demonstrated that fiber formation is preceded by the transition of several boluses of SCO-spondin-GFP labeled Reissner material down the central canal prior to the extension of the RF down the central canal (Figure 3L; Video S2). These movements appeared somewhat sporadic, as the RF material could stall in place for up to 20 min before continuing down the central canal. Motile cilia-dependent bi-directional CSF flow in zebrafish is first observed within the central canal at 24–26 hpf [20]. We speculate that the combination of bulk CSF secretion and its flow within the central canal is helping to push the bolus of RF material and the RF along the central canal. After the fiber is formed, during active axis elongation (between 2 and 3 dpf), we observed the dynamic breakdown of the RF in the terminal ampulla and distribution of SCO-spondin-GFP signal outward into the developing fin fold (Video S3).

It has long been suspected that the RF continually grows in a rostral-caudal direction throughout the life cycle [21], which is supported by the observations of rostral-caudal transport of radiolabeled-monoamines along the fiber in rat [22] and our observations of RF movement during embryonic development in *scospondin-GFP*$^{ut24/+}$ embryos (Figures 3F–3L). To directly quantify RF motility during zebrafish development, we photobleached the RF in the head and tail regions in *scospondin-GFP*$^{ut24/+}$ embryos (Figures 3B and 3D; Video S4). At all stages of development that we assayed, the photobleached regions

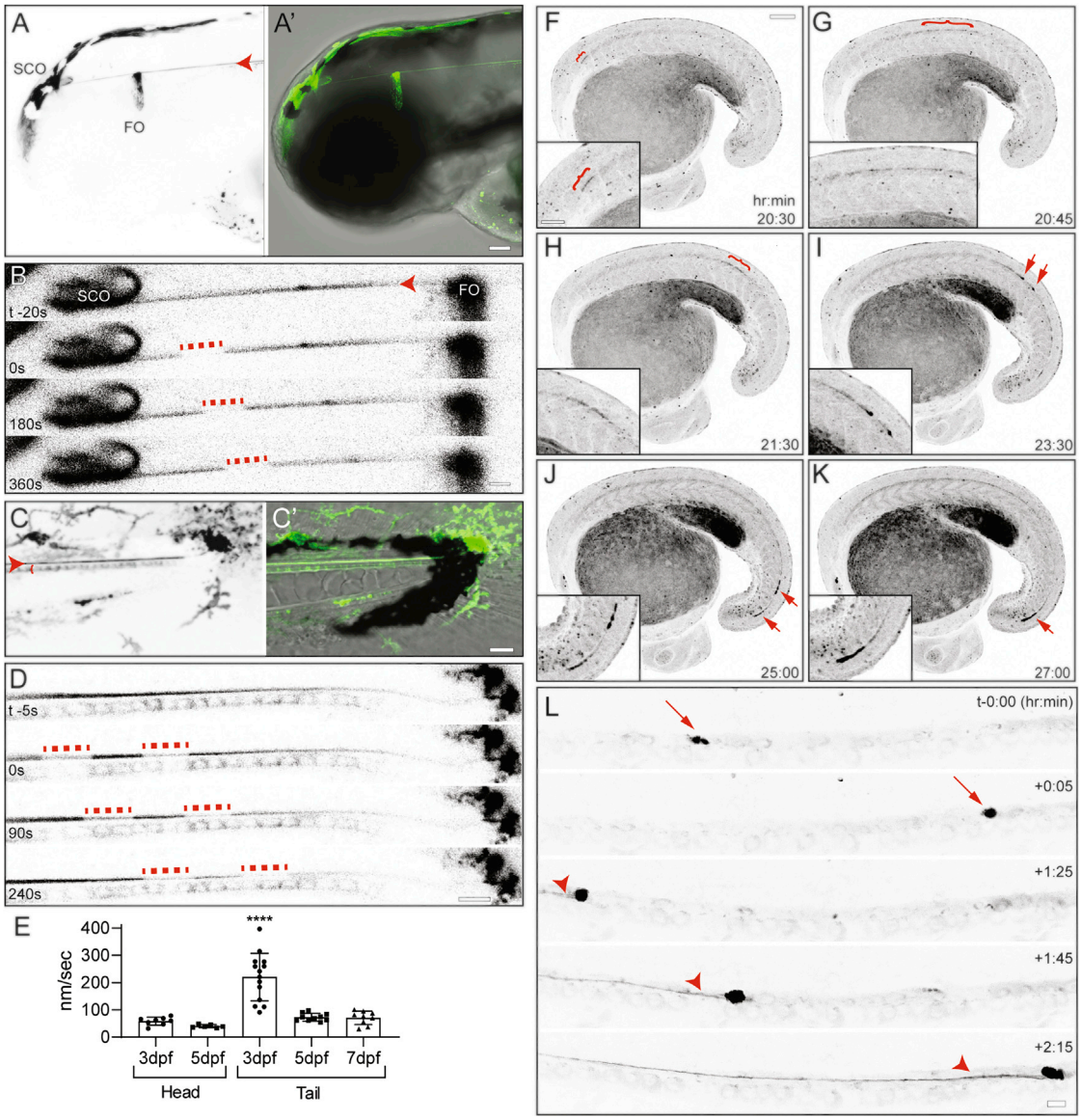

Figure 3. Dynamic Properties of the Reissner Fiber Revealed in *Scospondin-GFP^{ut24}* Knockin Zebrafish

(A) Inverted grayscale maximal Z projection of confocal stack of *scospondin-GFP$^{ut24/+}$* embryo at 3 dpf. Expression in the subcommissural organ (SCO) and flexural organ (FO) in the head with Reissner fiber (red arrowhead; A). Merge of differential interference contrast (DIC) image and pseudocolored SCO-spondin-GFP expression (green; A') is shown. Scale bar, 50 μm.

(B) Inverted grayscale frames from a time-lapse confocal dataset from a *scospondin-GFP$^{ut24/+}$* embryo head at 3 dpf. At time (t) = 0, a region was photobleached using a short, high-energy pulse from a 488-nm solid state laser, which allowed for manual tracking of the movement of the bleached region from rostral to caudal. Scale bar, 10 μm.

(C) Inverted grayscale maximal Z projection of confocal stack of *scospondin-GFP$^{ut24/+}$* embryo tail at 3 dpf. The Reissner fiber (red arrowhead) and floor plate (red bracket) are labeled with GFP (C). Merge of DIC image and pseudocolored SCO-spondin-GFP expression (green; C') is shown. Scale bar, 20 μm.

(D) Inverted grayscale frames from a time-lapse confocal dataset from a *scospondin-GFP$^{ut24/+}$* embryo head at 3 dpf. At time (t) = 0, two regions were photobleached as in (B), which allowed for manual tracking of the movement of the bleached region from rostral to caudal. Scale bar, 10 μm.

(E) Average velocity as nanometers (nm) per second (s) were calculated manually for multiple embryos at 3, 5, and 7 dpf in experiments depicted in (B) and (D) (n = 13, 9, and 8, respectively). The average velocity for each individual embryo was plotted as boxplots (mean ± SD; ****$p < 10^{-4}$).

(F–K) Single frames from a time-lapse confocal dataset taken during tail bud development (20–30 h post-fertilization; see Video S2) presented as inverted grayscale maximal Z projections. At the first indication of Reissner fiber formation (F–H), red brackets highlight fibers of SCO-spondin-GFP, which travel in a caudal direction. As development of the Reissner fiber roceeds (I–K) we observed the fiber could also accumulate as a bolus SCO-spondin-GFP material (red arrows), which could then travel rapidly in a rostral to caudal direction. Insets in the lower left-hand side of each panel are digitally enlarged portions of the region containing SCO-spondin-GFP-labeled material. Scale bars, 100 μm in main and 50 μm in inset. Time stamp is h:min post-fertilization.

(legend continued on next page)

of the RF consistently traveled in a continuous rostral to caudal direction in the brain (Figure 3B) and tail regions (Figure 3D). In the brain, we observed that the average speed of RF motility at 3 dpf was 58.6 ± 14.3 and at 5 dpf was 40.3 + 5.6 nm/s (Figures 3B and 3E). Within the tail region, we found the average speed of RF motility at 3 dpf was 220 ± 87 nm/s, although, at 5 and 7 dpf, the speed was markedly slower (70 ± 14 nm/s and 70 ± 24 nm/s, respectively; t test; $p = 1.3 \times 10^{-5}$; Figures 3D and 3E). Using high-speed imaging (10 Hz) at higher magnification, we also detected rapid movement of SCO-spondin-GFP-labeled puncta moving sporadically down the RF in a rostro-caudal direction, some of which occasionally extended away from the fiber toward the floor plate and retracted back into the bulk RF (Figure S3E; Video S5).

Our *in vivo* analyses of endogenous SCO-spondin-GFP expression and dynamics demonstrate several new properties of the RF, including (1) the initial secretion of Reissner material travels as punctate material from the brain, which precedes the elaboration of the fiber; (2) we directly confirm the hypothesis that the RF continually moves in a rostral-caudal direction at multiple stages of development; (3) we evidenced active breakdown of the RF at terminal ampulla; (4) the RF is a conduit for the rapid migration of substances in the CSF in a rostral-caudal direction; and (5) SCO-spondin secretion from the floor plate contributes to RF assembly. The *scospondin-GFP^{ut24}* knockin zebrafish line, which allows for analysis of dynamic properties of the RF *in vivo*, sets the stage for future studies aimed at defining molecular interactions of the Reissner fiber and the dynamics of central canal components with which the RF interacts to regulate axial morphogenesis.

Loss of the Reissner Fiber Is Associated with Scoliosis in Additional Independent Scoliosis Mutant Zebrafish Strains

As *scospondin-GFP^{ut24}* is an endogenous gene fusion of the wild-type *scospondin* locus, we are currently precluded from dynamic imaging of the RF in the hypomorphic *scospondin* mutants reported here. However, there are obvious phenotypic similarities between *scospondin* hypomorphic mutants and other cilia-related scoliosis mutants described previously [1, 2]. For this reason, we hypothesized that the loss of the RF may be a common phenotype associated with the onset of scoliosis in independent scoliosis mutant zebrafish in our collection. To test this, we first crossed *scospondin-GFP^{ut24}* to a dominant enhancer-trap transgenic scoliosis mutant, *Et(druk-GFP$^{dut26/+}$)* (R.S.G., A.R. McAdow, L.S.-K., and S.L. Johnson, unpublished data). This mutant was generated by a fortuitous, Tol2-GFP integration on *Danio rerio* chromosome 11, landing between the *MON1 secretory trafficking family member A* and *macrophage stimulating 1 receptor b* genes. *Et(druk-GFP$^{dut26/+}$)* fish also display a unique GFP-expression pattern in the brain and spinal cord (data not shown; Figure 4C'), which is tightly linked with the onset of axial curvatures around 15–18 dpf (Figure 4C) and adult-viable scoliosis (98%; n = 981). At 5 dpf, the majority of *Et(druk-GFP$^{dut26/+}$);scospondin-GFP$^{ut24/+}$* larvae showed a fully assembled RF (n = 6/6; Figures 4A and 4A'). At the onset of axial curvatures in these mutants, we observed a consistent loss of the SCO-spondin-GFP-labeled RF (100% of fish at 6.1–7.0 mm; n = 9; Figures 4D and 4D'). In contrast, similarly sized *scospondin-GFP$^{ut24/+}$* knockin larvae always displayed a typical RF (100% of fish sized 6.3–6.8 mm; n = 9; Figures 4B and 4B'). Although the molecular genetics of the dominant *Et(druk-GFP$^{dut26/+}$)* scoliosis mutant remains to be defined, we do provide direct evidence that the disassembly of the SCO-spondin-GFP-labeled RF in real time, in a living animal, is coincident with the onset of axial curvatures and scoliosis in these mutants.

Mutations in the zebrafish *kinesin family member 6* (*kif6*) gene cause scoliosis without vertebral malformations in adult zebrafish. We first assayed the RF using AFRU immunostaining in *kif6$^{sko/sko}$* mutants at 1 dpf and found no defects in the assembly of the RF, in comparison to heterozygous *kif6$^{sko/+}$* control embryos (Figures 4E and 4F). By 3 dpf, *kif6$^{sko/sko}$* mutant embryos display mild axial curvatures [23]; concurrently, we observed the complete disassembly of the RF (Figure 4H) within the central canal (Figure 4H'). In contrast to the absent or diffuse staining observed in *scospondin^{stl297}* mutants (Figures 2E''' and 2F), we consistently detected the AFRU-stained Reissner material filling up the entire central canal in *kif6^{sko}* mutants at both 3 and 5 dpf (Figures 4H'' and 4J), suggesting that the secretion of the material is not affected; rather, its ability to polymerize in the central canal is disrupted. Defects in motile cilia components give rise to defects in RF formation in zebrafish embryos [3], and the motile ciliated ependymal cell cilia are lost in adult *kif6* mutants [1]. This suggests that alterations in CSF flow may underlie the loss of RF polymerization in *kif6^{sko}* mutants. However, bulk CSF flow is grossly unaffected in *kif6* mutant embryos [23], suggesting alternative models of *kif6* regulation for RF assembly are possible. Altogether, our observations of RF disassembly in three independent scoliosis mutants strongly support the critical role of the RF structure to regulate the homeostasis of the straight body axis and for spine morphogenesis in zebrafish. Additional studies focused on the elucidation of cellular and molecular differences related to RF disassembly in these three independent scoliosis mutant strains are warranted.

Since the discovery of the RF, multiple hypotheses have been proposed for its function, including detoxification and transport of molecules in CSF [22], neurogenesis during early brain development [24, 25], and through its direct interaction with the ciliated CSF-contacting neurons lining the central canal, as a mechanosensory organ controlling the "flexure of the body" [26, 27]. Early work in amphibians demonstrated that the resection of the SCO disrupted RF assembly and led to scoliosis in some animals [28, 29]. Here, we used forward genetics and cell biology approaches in zebrafish to demonstrate that two evolutionally conserved cysteine residues in the SCO-spondin protein are critical for stability of the RF during larval development. One of these cysteines (C2262) is predicted to form a disulfide bridge in one of several canonical LDL receptor A

(L) Frames from a time-lapse confocal dataset taken during tail bud development (20–22 h post-fertilization; see Video S2) presented as inverted grayscale maximal Z projections. Red arrows highlight SCO-spondin-GFP-labeled bolus material, although red arrowheads indicate bolus material leading the Reissner fiber. Scale bar: 10 μm.

See also Figure S3 and Video S1, S2, S3, S4, and S5.

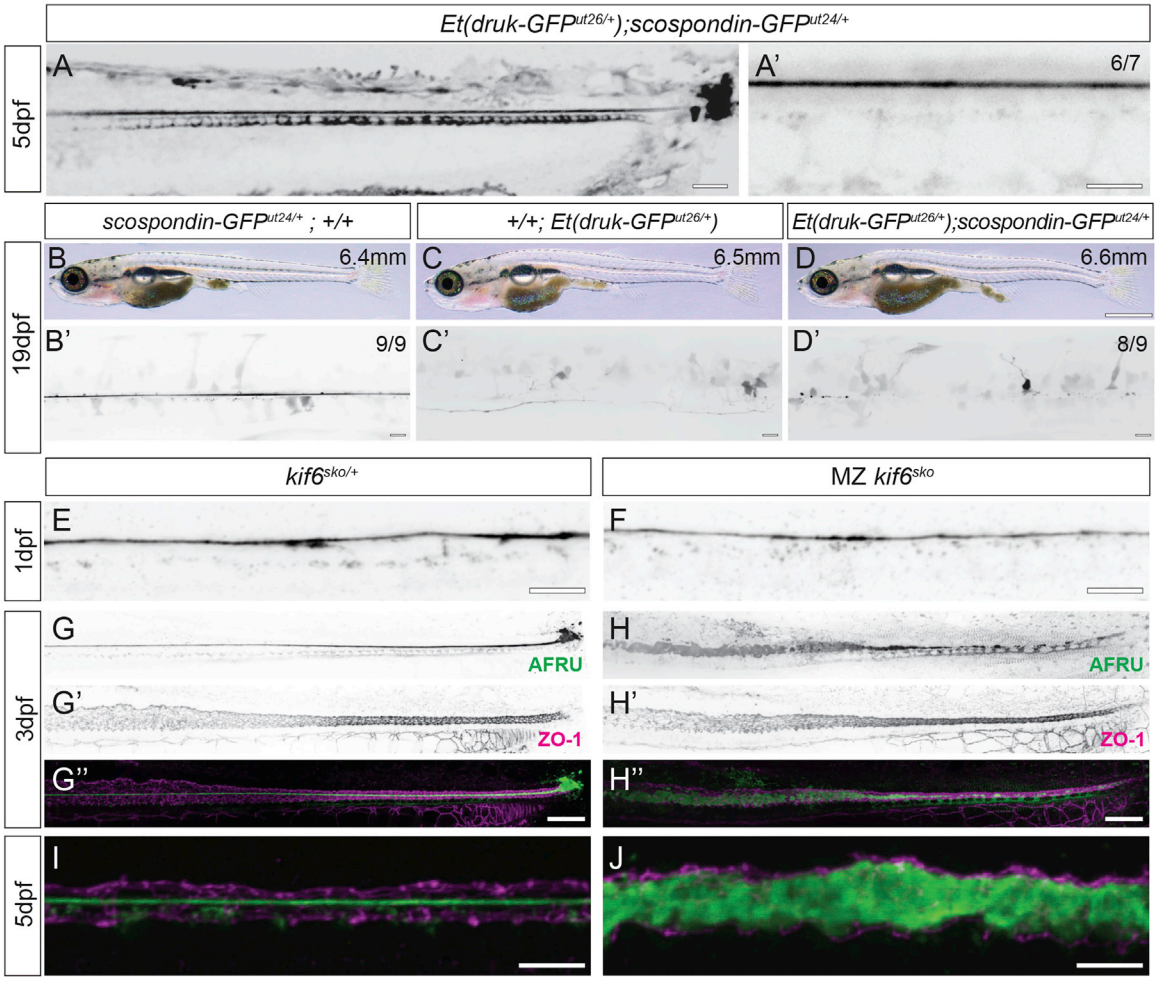

Figure 4. Loss of the Reissner Fiber Is Associated with Scoliosis in Additional Independent Scoliosis Mutant Zebrafish Strains

(A and A') Inverted grayscale maximal Z projections of confocal images of *Et(druk-GFP$^{dut26/+}$); scospondin-GFP$^{ut24/+}$* demonstrating typical assembly of the Reissner fiber, floor plate, and terminal ampulla expression in these mutant knockin embryos at 5 dpf. *Note that GFP expression is contributed both by the Et(druk-GFP$^{dut26/+}$) transgene insertion and from the scospondin-GFP$^{ut24/+}$ allele.* Scale bars, 25 μm in (A) and 5 μm in (A').

(B–D) Bright-field images of a wild-type juvenile *scospondin-GFP$^{ut24/+}$* (B), *Et(druk-GFP$^{dut26/+}$)* (C), and *Et(druk-GFP$^{dut26/+}$); scospondin-GFP$^{ut24/+}$* (D) displaying the onset of mild scoliosis. Scale bar, 1 mm; standard length in upper right corner. (B'–D') Inverted grayscale maximal Z projections of confocal images of the same fish in (B), (C), and (D) to highlight the spinal cord are shown. At 19 dpf, in wild-type *scospondin-GFP$^{ut24/+}$*, we observe high expression of the Reissner fiber (100%; n = 14 size range 6.3–6.8 mm; B'); in scoliosis mutant *Et(druk-GFP$^{dut26/+}$); +/+*, the Reissner fiber is not labeled but some spinal cord cells express GFP (n = 6 size range 6.0–6.5 mm); and in double mutant *Et(druk-GFP$^{dut26/+}$); scospondin-GFP$^{ut24/+}$*, we observed curvature of the spinal canal and a complete loss of a Reissner fiber (94%; n = 16 size range 6.1–7.0 mm). Scale bars, 25 μm.

(E and F) Inverted grayscale maximal Z projections from confocal imaging of AFRU-stained zebrafish embryos at 1 dpf (30 hpf). The Reissner fiber is observed in heterozygous kinesin family member 6 (*kif6$^{sko/+}$*) (E) and homozygous *kif6^{sko}* mutants (F) (8/8; for each genotype). Scale bars, 10 μm.

(G–H'') Inverted grayscale maximal Z projections of confocal imaging of AFRU- and ZO-1-stained zebrafish at 3 dpf. ZO-1 localizes to tight junctions and shows the location of the central canal epithelium. Heterozygous *kif6$^{sko/+}$* animals have an intact Reissner fiber in the central canal (13/13; G–G''), whereas in homozygous *kif6^{sko}*, the Reissner fiber is disassembled and Reissner material fills the space of the central canal (12/13; H–H''). Scale bars, 25 μm.

(I and J) Merge of maximal Z projections of confocal imaging of AFRU- and ZO-1-stained zebrafish at 5 dpf. Heterozygous *kif6$^{sko/+}$* animals have an intact Reissner fiber in the central canal (I), but in homozygous *kif6^{sko}* animals, diffuse Reissner material fills the central canal lumen (J). Scale bars, 10 μm.

domains found in SCO-spondin. Interestingly, the LDL protein apolipoprotein B has been directly visualized in the central canal in zebrafish [30] and is found in the CSF of rat and humans by proteomic analysis [31–33]. Apolipoprotein B is also an important neurogenic factor *in vitro* [34], is important for brain development in mice [35], and forms a complex with SCO-spondin in the CSF, which can synergistically modulate neurodifferentiation in organotypic brain culture [36]. For these reasons, it is tempting to speculate that the C2262S mutation may also disrupt important LDL interactions with the Reissner fiber, causing alterations in neuronal differentiation in *scospondin^{stl297}* mutant zebrafish.

Our results using a variety of genetic models of scoliosis in zebrafish, a novel *scospondin-GFP* knockin strain, and analysis of cell biology and time-lapse imaging approaches to assay the RF *in vivo* now demonstrate that the intact fiber and its

dynamic properties are required for maintaining a straight body axis and spine morphogenesis. Our study opens up a new field of exploration of dynamic properties of the Reissner fiber assembly, of molecular interactions of the fiber and CSF components for axial morphogenesis, and whether this physiology is driving scoliosis in humans.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.cub.2020.04.015.

A video abstract is available at https://doi.org/10.1016/j.cub.2020.04.015#mmc8.

ACKNOWLEDGMENTS

We thank Esteban Rodriguez and Maria Montserrat Guerra (Universidad Austral de Chile) for their generous gift of the AFRU antiserum. We thank Chole Rose and Brian Ciruna for generously sharing the *scospondin*^{hsc105} mutant zebrafish prior to publication. We thank Sierra Szkrybalo and Melisa N. Bayrak for assistance with zebrafish experiments. We thank Drs. John Wallingford and Claire Wyart for critical comments on this manuscript. We thank the Genome Technology Access Center in the Department of Genetics at Washington University School of Medicine for help with genomic analysis. The center is partially supported by NCI Cancer Center Support Grant no. P30 CA91842 to the Siteman Cancer Center and by ICTS/CTSA grant no. UL1TR002345 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research. This publication is solely the responsibility of the authors and does not necessarily represent the official view of NCRR or NIH. Research reported in this publication was supported in part by a grant from Spinal Cord Injury/Disease Research Program (SCIDRP) (to L.S.-K. and Steve Johnson), the Scoliosis Research Society (SRS), the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the NIH under award number AR072009 to (R.S.G.) and AR066061 to (R.Y.K.), and by the National Institute of Child Health and Human Development of the NIH under award number P01HD084387 (L.S.-K.).

AUTHOR CONTRIBUTIONS

R.S.G., D.S.S., and L.S.-K. set up the forward genetic screen and isolated the *scospondin* mutant alleles; P.G. and R.S.G. performed WGS/WES and mapping of the mutants; A.M.-R. and R.Y.K. performed microCT imaging and analysis; B.R.T. and M.J.K. performed immunohistochemistry, confocal imaging, and statistical analysis; B.R.T. engineered the *scospondin-GFP* knockin, with help with screening and genotyping by R.M.; and R.S.G. and L.S.-K. funded and supervised the project. R.S.G. conceived the project and wrote the article with input from B.R.T., R.Y.K., D.S.S., and L.S.-K.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: November 8, 2019
Revised: February 29, 2020
Accepted: April 6, 2020
Published: May 7, 2020

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Antibodies		
Rabbit anti-bovine Reissner fiber antiserum	Gift from Esteban Rodriguez and Maria Montserrat Guerra (Universidad Austral de Chile)	AFRU
Chicken anti-GFP	Abcam (ab13970)	RRID:AB_300798
ZO-1 Monoclonal Antibody (ZO1-1A12)	Thermo Fisher (33-9100)	RRID:AB_2533147
Goat anti-Rabbit IgG (H+L) Alexa 488	Thermo Fisher (A11034)	RRID:AB_2576217
Goat anti-Rabbit IgG (H+L) Alexa 555	Thermo Fisher (A21428)	RRID:AB_2535849
Goat anti-Chicken IgY (H+L) Alexa 488	Thermo Fisher (A11039)	RRID:AB_2534096
Goat anti-Mouse IgG1 Alexa 647	Thermo Fisher (A21240)	RRID:AB_2535809
Chemicals, Peptides, and Recombinant Proteins		
EnGen Spy Cas9 NLS	New England Biolabs	M0646
Critical Commercial Assays		
CloneAmp Hif PCR Mastermix	Takara Bio	ST0506
5X In-Fusion HD Enzyme Premix	Takara Bio	ST0345
HiScribe T7 High Yield RNA Synthesis Kit	New England Biolabs	E2040S
Deposited Data		
WGS/WES data	SRA browser	GSE138920
Experimental Models: Organisms/Strains		
scospondin^{UT24}	This manuscript	N/A
scospondin^{stl297}	This manuscript	N/A
scospondin^{stl300}	This manuscript	N/A
Oligonucleotides		
See Table S1	This manuscript	N/A
Recombinant DNA		
pCS108-scospondinGFP donor	This manuscript	N/A
Other		
Fiji	[37]	https://fiji.sc/
GraphPad Prism	GraphPad	https://www.graphpad.com/scientific-software/prism/
FishCUT	[15]	https://github.com/elifesciences-publications/FishCuT

LEAD CONTACT AND MATERIALS AVAILABILITY

Further information and requests for *scospondin* mutants (*stl297* and *stl300*), *scospondin-GFP*^{ut24} knock-in zebrafish, or pCS108-*scospondinGFP* donor targeting reagents should be directed to and fulfilled by the Lead Contact Lead Contact, Ryan S. Gray (ryan.gray@austin.utexas.edu).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Zebrafish Maintenance and Care

All experiments were performed according to University of Texas at Austin with approval of the IACUC committee. All experiments were performed on *Danio rerio* embryos or larval – adult fish of the AB background. Animals were raised at 28.5°C under a 14/ 10 light/ dark cycle until the start of experiments.

METHOD DETAILS

WGS / WES analysis

Phenotypic, mutant zebrafish were pooled and submitted for sequencing. Non-phenotypic wild-type and heterozygous siblings were pooled together and submitted for sequencing. Raw reads were aligned to zebrafish genome GRCz10 using bwa mem (v0.7.12-r1034) with default parameters and were sorted and compressed into bam format using samtools (v1.6) [38]. Variants were called using bcftools (v1.9) functions mpileup, call, and filter. mpileup parameters "-q 20" and "-Q 20" were set to require alignments and base calls with 99% confidence to be used and filter parameters "-s LowQual -e '%QUAL<20'" were used to remove low quality variant calls. Variants were then annotated and filtered by an in-house pipeline. Briefly, variants occurring with the same allele frequency between phenotypic and aphenotypic samples were filtered from further analysis as were variants that were not called as being homozygous in the phenotypic sample. Variants in the mutant samples that were homozygous for the wild-type allele were also excluded. Variants found in the dbSNP database (build v142) of known variants were also filtered out and excluded from further analysis. The wild-type and mutant alleles at each variants site were tabulated, and the Fisher p value was calculated for each variant site. These remaining variants classified based on their genomic location as being noncoding site variants, coding site variants, or variants that may affect gene splicing using zebrafish Ensembl annotation build v83. For coding site variants, the amino acid of the wild-type allele and the mutant allele were determined from the Ensembl annotation. The p values were plotted against genomic location, and a region of homozygosity in the genome with a cluster of small p values was found. Variants occurring within this region of homozygosity were manually prioritized for nonsynonymous mutations in genes.

MicroCT scanning and analysis

MicroCT scanning was performed as previously described [15]. All analyses were performed in precaudal and caudal vertebrae only (we refer to the 1st precaudal vertebrae as vertebra 1). For analysis of spinal curvature, centrum centroid positions were identified in maximum intensity projections. A line was drawn connecting the first and last vertebrae. The absolute value of the displacements from this line were computed in the sagittal and frontal planes to compute Sagital Displacement (Sag.Disp) and Lateral Displacement (Lat.Disp) for vertebrae 1-20. For analysis of bone, FishCuT was used to quantify Length (Le), Volume (Cent.Vol), Tissue Mineral Density (TMD), and Thickness (Th) in the Centrum (Cent), Neural Arch (NA), and Haemal Arch (Haem) for vertebrae 1-16 [15]. Computation of standard scores, z-scores, and statistical testing using the global test were performed as previously described [15, 39].

Generation of endogenously tagged scospondin-GFP^{ut24} allele

CRISPR/Cas9 targets were chosen using CHOPCHOP and guides were synthesized according to the CHOPCHOP protocols [40]. The last exon of *scospondin* was targeted with the CRISPR guide AGTGTACCAGCTGCCAGGGTGGG (PAM underlined) predicted to cut 6 bp upstream of the stop codon. To generate an sgRNA guide, an oligo (Scospondin_stop_sgRNA) containing a T7 promoter, gene-specific targeting sequence, and annealing region was synthesized (Sigma-Aldrich). This oligo was annealed to a generic CRISPR oligo using CloneAmp Hifi Polymerase. RNA was synthesized using the NEB HiScribe T7 RNA synthesis kit and purified with the Zymo RNA Clean and Concentrator-5 kit.

A plasmid was constructed to serve as a donor. The plasmid contained 5′ and 3′ homology arms (776 and 532 bp respectively) flanking the eGFP coding sequence (720bp). The donor was constructed such that the PAM would be abolished and the eGFP coding sequence would be inserted just before the endogenous stop codon. The homology arms were cloned from wild-type AB zebrafish DNA and eGFP was cloned from the p3E-2AnlsGFP plasmid [41] using Clontech Hifi polymerase mix. These three fragments were purified (NucleoSpin Gel and PCR Clean-up, Machery-Nagel #740609) and Gibson cloned into the EcoRI site of pCS108 using the In-Fusion HD Cloning kit (Clontech) following manufacturer protocols.

Wild-type AB zebrafish were incrossed and one-cell embryos were injected with 1nL of injection mix containing 5μM EnGen Spy Cas9 NLS (NEB #M0646), 100 ng/μL sgRNA, and 25 ng/μL donor plasmid. Once the embryos reached adulthood, sperm was collected from F0 males and DNA was extracted by diluting sperm into 50uL of 50mM NaOH and heated to 95°C for 40 minutes, then neutralized with 10uL 1M TRIS. PCR was performed with GFP-specific primers using GoTaq Green Master Mix (Promega #M7123). Males that generate an amplicon after PCR were outcrossed to WT AB females, and the progeny were screened for GFP expression in the SCO and Reissner Fiber.

Skeletal preparation

Animals were euthanized in tricaine and fixed in 10% formalin overnight, then incubated in acetone overnight. Acetone was washed away with water, and animals were stained with Bone/Cartilage Stain (0.015% Alcian Blue, 0.005% Alizarin Red, 5% Acetic Acid, 59.5% Ethanol) at 37°C overnight, and cleared in 1% KOH for days to weeks depending on the size of the fish. The fish were then moved to 25%, 50%, and then 80% glycerol and imaged.

Immunohistochemistry and live imaging

Animals were euthanized with high dose tricaine (MS-222), and then fixed in sweet paraformaldehyde solution (4% PFA, 4% sucrose in PBS) for 2 hr at 4°C. Animals were washed in PBSTr (1x PBS with 0.1% Triton X-100), blocked with 10% normal goat serum in 1x PBS with 0.5% Triton X-100 and 1% DMSO. The following primary antibodies were used as follows: Rabbit AFRU primary antibody

shared by Esteban Rodriguez (Rodríguez et al., 1984) and at 1:2000 dilution, Mouse anti ZO-1 (Thermo-Fisher #33-9100, RRID: AB_2533147) at 1:250 dilution, and Chicken anti GFP (Abcam ab13970, RRID: AB_300798) at 1:500 dilution in blocking solution overnight at room temperature. Specimens were then washed and stained with the following secondary antibodies at 1:1000 in block: goat anti-rabbit IgG (H+L) Alexa Fluor 488 (Thermo Fisher Cat# A11034, RRID:AB_2576217), goat anti-rabbit IgG (H+L) Alexa 555 (Thermo Fisher Cat# A21428, RRID:AB_2535849), goat anti-chicken IgY (H+L) Alexa 488 (Thermo Fisher Cat# A11039, RRID:AB_2534096), goat anti-mouse IgG1 Alexa 647 (Thermo Fisher Cat# A21240, RRID:AB_2535809); then washed in PBSTr and counterstained with DAPI. Fixed specimens were immobilized in 1% low-melt agarose in 1x PBS. Live embryos or larvae were anaesthetized in 0.16% tricaine for 10 minutes and then embedded in 0.5% low-melt agarose, 0.16% tricaine in egg water for imaging using a humidified incubating stage set to 28.5°C. All confocal images were taken using a Nikon Ti2E / CSU-W1 spinning disc confocal system, with the exception of photobleaching experiments which were performed using a Nikon A1R laser scanning confocal microscope. Post-acquisition analysis was done using standard modification of levels of the entire image file (Nikon .nd2 file) and exported as jpeg's in Fiji (ImageJ).

QUANTIFICATION AND STATISTICAL ANALYSIS

Statistical analysis was performed using GraphPad Prism, and statistical details are given in figure legends.

DATA AND CODE AVAILABILITY

The published article includes all datasets generated or analyzed during this study.